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Integration of Taguchi's Robust Parameter Design Approach in a Mature Lean Manufacturing Environment - The Case of the Apparel Industry

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in
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Abstract

It has been documented in the literature that combining overlapping manufacturing practices lead to superior performance. The primary driver of this study is the conceptual overlap the researcher identified between the zero waste proposition in Lean and the zero defects (loss to society) proposition in Taguchi's Quality Philosophy (TQP); TQP provides the backbone of Taguchi's robust parameter design (RPD) approach, a statistically driven experimental method that enables engineers to identify optimum design parameter settings to make the product's functionality robust against the background variables (noise). This study hypothesises that Taguchi's RPD approach complements Lean. This overall hypothesis was examined in two phases.

First, through the literature, the researcher hypothesised the theoretical relationships between TQP and Lean, through the mediating role being played by Continuous Improvement to explain Manufacturing Outcomes. This model was tested through Structural Equation Modelling using data collected from 318 respondents in 31 apparel manufacturing factories belonging to a mature Lean organisation in Sri Lanka. The researcher found that the model was a good fit to data (e.g. RMSEA = 0.047), which suggested that her hypothesised theoretical model is tenable and that TQP is acceptable to Lean practitioners as an avenue to improve manufacturing performance.

Next, the researcher examined the practical compatibility between Taguchi's RPD approach and Lean through extensive fieldwork in one of the factories in the Lean organisation. The work involved conducting RPD experiments to solve a substantial quality problem, (which helped the researcher to identify the merits and demerits of Taguchi methods) and also permitted ethnographic engagement with the factory staff. This enabled the researcher to explore the drivers and restraints of integrating Taguchi's RPD in the setting studied. The merits of Taguchi's RPD were found to be the high degree of standardisation, ease of conducting the experiment and analysing the data, and compatibility with the Lean culture. The researcher identified 5 drivers (also 3 inhibitors) out of which, the most influential drivers were: (a) the experienced ineffectiveness of the existing tools and techniques being used, (b) non-value adding activities associated with machine setting up, and (c) conduciveness to conduct large Taguchi style experiments. Using *Force Field Analysis* as the theoretical framework, the researcher explained how Lean organisation, similar to the one being considered, can move towards using Taguchi's RPD as a tool for process improvement. The study identified several future research directions for practitioners and academics.

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List of Acronyms

AIAG	American Automotive Industry Action Group
AMOS	Analysis of Moment Structures
ANOVA	Analysis of Variance
AQL	Acceptable Quality Level
CBSEM	Covariance Based Structural Equation Modelling
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
CI	Continuous Improvement
DoE	Design of Experiments
LHS	Left Hand Side
LSL	Lower Specification Limit
MSD	Mean Square Deviation
MSE	Mean Square Error
NFI	Normed Fit Index
NPP	Normal Probability Plot
OA	Orthogonal Array
PCA	Principal Component Analysis
PCLOSE	The Closeness of Fit
PDCA	Plan-DO-Check-Act
PLSBSEM	Partial Least Squares Based Structural Equation Modelling Approach
QA	Quality Assurance
QCO	Quick-Change-Over
QI	Quality Improvement
RD	Robust Design
RE	Robust Engineering
RHS	Right Hand Side
RMSEA	Root Mean Square Error of Approximation
RPD	Robust Parameter Design
SD	Standard Deviation
SEM	Structural Equation Modelling
SNR	Signal-to-Noise Ratio
SPI	Stitches Per Inch
TMC	Toyota Motor Corporation
TPS	Toyota Production System
TW	Toyota Way
USL	Upper Specification Limit

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CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION

Rapid globalisation of products and markets in the twenty-first century means that manufacturing competitiveness is becoming an ever increasing requirement. Firstly, a manufacturer needs to produce the right product, at the right time, at the right price, to the right customer, meeting the expectations of the key stakeholders to achieve manufacturing process effectiveness (Kaplan, 1992; Wincel & Kull, 2013). Secondly, the manufacturer needs to produce the product in a cost effective manner to achieve manufacturing process efficiency (Kaplan, 1992; Wincel & Kull, 2013). Conventionally, manufacturers strive to improve process efficiency, among other things, by making their products conform to specifications (conformance quality) and using their resources optimally (Summers, 2010). Implicit in this conventional quality control approach is the notion that as long as the product's functional characteristic falls anywhere within the tolerance band specified by the customer, there is no non-conformity, quality is achieved, and hence there is no loss to either the producer or the end customer.

In the 1980s the Japanese engineer turned quality guru Genichi Taguchi (1924-2012) revolutionised the meaning of quality control in the west by adding a new paradigm to quality. This paradigm, which is commonly known as Taguchi's robust parameter design (RPD) approach views conventional quality control (i.e. conformance to specifications) as inefficient and ineffective in assuring superior product quality in a competitive environment. This study examines the applicability of the RPD approach in apparel manufacturing environments that utilise mature Lean manufacturing techniques (an explanation follows) using multiple streams of data and research techniques (data and methods triangulation).

1.2. BACKGROUND OF THE STUDY

Researchers have shown the importance of integrating a mix of different but overlapping manufacturing practices to achieve and sustain manufacturing competitiveness (Flynn, Sakakibara, & Schroeder, 1995; Pullan, Bhasi, & Madhu, 2011). The apparel industry has been Sri Lanka's largest gross export earner since 1986 (Dheerasinghe, 2003) and hence it is the leading industry sub-sector (Weeraratne, 2004). Currently the apparel industry contributes 43% towards Sri Lanka's total export earnings (EDB, 2014). Sri Lankan apparel companies that are successful in the global market are the ones that are able to provide high quality apparel at improved productivity (e.g. better use of machinery, time, and less rework).¹ One such Sri Lankan apparel company that stands out in the global market is the organisation in which the researcher conducted her case study. This organisation is a mature Lean apparel manufacturing organisation, which chose "Lean" as their competitive strategy ten years ago. There are many parallels between the Lean operations system used in Toyota Motor Corporation, Japan and the Lean operations system adapted by the case study organisation. In this thesis the researcher argues that deploying Taguchi's RPD approach results in manufacturing practices that overlap Lean manufacturing practices to enhance manufacturing performance. It is the overall hypothesis that the researcher empirically tests using rigorous research techniques (an overview of the methodology is provided in section 1.7).

1.2.1. Robust Design Methodologies

Robust Engineering (RE) or Robust Design (RD) can be defined as an engineering approach that aims to minimise sensitivity of products and processes to variations that transmit from external and internal environmental factors (e.g. the user conditions, temperature, variability of material) (Box & Bisgaard, 1987; Box, Bisgaard, & Fung, 1988; Roy, 2010). RE based on statistically designed experiments—more commonly known as design of experiments or DoE—to identify optimum production parameter

1 Sri Lanka's per capita income (US\$ 6,500.00 approx.) is much higher than the per capita income of their neighbors (e.g. Bangladesh – US\$ 2,000.00 approx. and India – US \$ 4,000.00 approx.) who also have a strong apparel manufacturing sector. High wage rates means that Sri Lankan apparel sector needs to continuously improve their production efficiency and effectiveness to compete with their similar countries that offer lower wage rates to the workers.

settings (i.e. the RPD approach) to operate a process is a revolutionary approach in quality engineering. As Genichi Taguchi, asserted “the robustness of products are more a function of good design than of on-line quality control” (Taguchi & Clausing, 1990).

Since Taguchi published his Quality philosophy and the associated DoE methods in the mid-1980s to achieve the robustness in products and processes, DoE received an increased attention among both practitioners and statisticians (Nair et al., 1992; Song, Mathur, & Pattipati, 1995). Practitioners, particularly the engineers, paid attention to the DoE methods prescribed by Taguchi because these were presented in a language that is understood and preferred by them. Academia paid attention to Taguchi’s RPD approach because it brought a new paradigm/philosophy on quality and invited scholars the opportunity to review the DoE methodologies prescribed by Taguchi (for details see sections 3.4.1 and 3.4.2 in Chapter 3). Consequently, DoE as a discipline became enriched by both Taguchi’s approach and subsequent approaches proposed by statisticians as alternative RPD approaches (Engelhardt, 2001; Khuri & Mukhopadhyay, 2010; Montgomery, 2013). Figure 1.1 shows the number by publications (by year) found in the article database Scopus (up to end of 2014) containing the search word “Taguchi Methods” in the *article title* or *abstract* or *key words*. The figure shows that there is no slowing down on the interest on Taguchi methods by the research community.

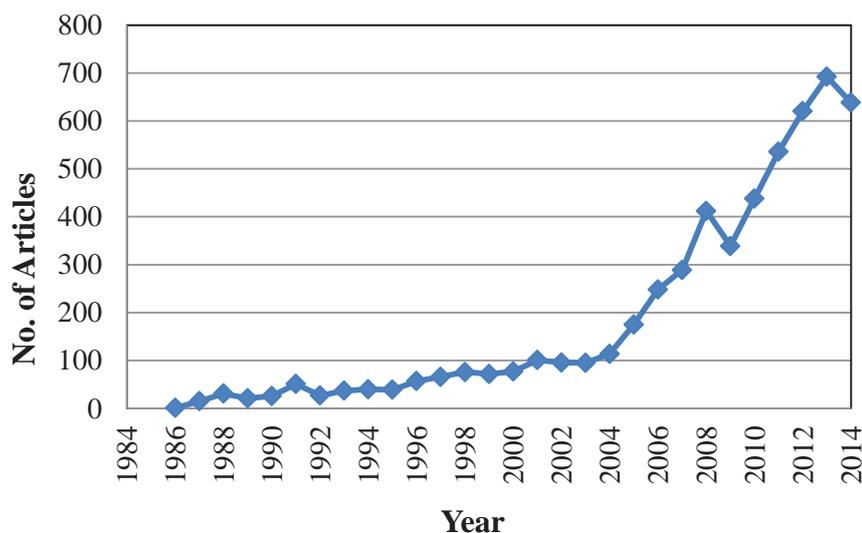


Figure 1.1: Articles found in Scopus containing the search word “Taguchi methods”

Genichi Taguchi was a Japanese engineer who worked for many different industries in Japan, China, US, and other countries (Myers, Khuri, & Vining, 1992; Taguchi, Chowdhury, & Wu, 2005) as a quality consultant. He is widely regarded as the father of RD (or RE). Taguchi introduced his philosophical paradigm and the associated DoE methodology in Japan (from 1950s through to 1980s) to improve the quality of Japanese products (Montgomery, 2013; Nair et al., 1992; Taguchi et al., 2005). In the mid-1980s they became known to the western world through the publications on Taguchi methods. In Japan, Taguchi received the same respect as Deming did for contributing to the knowledge and knowhow of the Japanese industry (Gunter, 1987; Sullivan, 1987; Taguchi et al., 2005).

Taguchi's philosophical view about building quality in a product (or process) by minimising variation (building robustness) was a revolutionary idea in quality engineering that challenged the traditional quality control methods (Gunter, 1987; Roy, 2010; Taguchi, Chowdhury, & Taguchi, 2000). In particular, Taguchi argued that any deviation of the functional characteristic (quality characteristic) of a product from its desired value (target value) causes an overall "loss to society", the loss being proportional to the squared difference between the observed value and the desired value (Gunter, 1987; Roy, 2010; Taguchi et al., 2000). Whereas the conventional quality planning and quality control is based on the notion that a capable process would result in a product (or process) whose quality characteristic would stay anywhere within the specified tolerance range (specification limits), nearly all the time, quality planning and control based on Taguchi's RPD approach is based on the notion that variation needs to be minimised by attempting to minimise the loss to society by making the quality characteristic to stay at the target value as close as possible (Gunter, 1987; Roy, 2010; Taguchi et al., 2000).

Taguchi's Quality Philosophy (loss to society) and his methods to design a product (process) to be insensitive to the variability of the uncontrollable factors (noise factors) using DoE methods (commonly known as Taguchi methods) have been welcomed by scholars as well as practitioners. However, some scholars (especially the statisticians) have criticised (details in section 3.4.2 in Chapter 3) the DoE tools and techniques prescribed by Taguchi to achieve a robust design (Boylan & Cho, 2013; Mandal, 2012; Zang, Friswell, & Mottershead, 2005).

Taguchi methods are based on the assumption that it is the engineer and not the statistician who drives the experiment (Sarin, 1997; Taguchi et al., 2000). Alternative DoE approaches to achieve a robust design subsequently prescribed by the statisticians are based on the reverse assumption (i.e. it is statistician who drives the experiment). Consequently, it is reasonable to advance that some situations may favour Taguchi methods while other situations may favour alternative DoE methods. Some research objectives of this study (see objectives 2 and 3 in section 1.6.2) are based on this proposition.

1.2.2. Lean Production Systems

Lean is one of the most influential manufacturing paradigms prevailing in the 21st century (Hines, Holweg, & Rich, 2004; Holweg, 2007; Pullan et al., 2011). The term “Lean production” was coined by John Krafcik in 1988 while he was working as a quality engineer in Toyota’s *New United Motor Manufacturing, Inc.* (NUMMI) plant in California (Shah & Ward, 2007). Womack and Jones (2003), the authors of one of the two bestselling books “Lean Thinking”, which examines the operational success of the Toyota Production System (TPS), have made the terms “Lean” and “Lean production” popular to the outside world (Holweg, 2007; Morgan & Liker, 2006)².

Lean manufacturing originated in Japan at the Toyota Motor Corporation (TMC), the world’s largest automobile manufacturer (the TMC was founded by Kiichiro Toyoda in 1937). The TPS caught the attention of the western world when the benefits of the TPS became more apparent to the world outside Japan. The benefits came not so much because of customer attraction to the design (e.g. style) or performance of the automobiles that Toyota produced, but because of the customer benefits such as reliability and durability that resulted from the incredible consistency and precision levels the TPS achieved in manufacturing (Liker, 2004). TPS/Lean Production has received attention from the academia and the industry due to its uniqueness (details in Chapter 2) and the ability to bring about significant gains to Toyota and a variety of other manufacturing and service organisations within and outside the automobile industry (Hines et al., 2004; Holweg, 2007).

² The other bestselling book that created great interest about Lean is the book titled “The Machine that Changed the World” by Womack, Jones, and Ross (1990).

Lean manufacturing is a set of manufacturing practices (Jayaram, Das, & Nicolae, 2010; Shah & Ward, 2007) that have been brought forth through application of tools and techniques such as Just-In-Time, Kaizen, One-Piece-Flow, Jidoka, Heijunka, Shingo-Shingo/Single Minute Exchange of Die (SMED) system that were developed under the leadership of late Taiichi Ohno at the TMC, Japan (Hines et al., 2004; Liker, 2004). Lean can also be viewed as an operational philosophy of adding value to the customer by eliminating waste and non-value adding activities from all aspects of production (Hines et al., 2004; Womack & Jones, 2005b). In Lean manufacturing, tools and techniques such as the aforementioned, as well as the associated socio-technical system act as the vehicle in eliminating waste and non-value adding activities (details in Chapter 2).

1.3. THE APPAREL INDUSTRY IN SRI LANKA

Sri Lanka, formally known as Ceylon (prior to 1972), is a tiny island (65,610 km²) south of India, with a population of 20.8 million. Abundance of natural resources (arable land, spices, minerals etc.) in Sri Lanka and its strategic location (e.g. to establish an administrative hub to control India during the colonial era, falling in the pathway of a busy international maritime transport route) meant that Sri Lanka was subjected to foreign occupation by the Portuguese (1505-1638), Dutch (1638-1796), and the British (1796-1948). The European rulers (particularly the British) went to great lengths in introducing and growing tea, rubber and coconuts for export purposes; in fairness to them (particularly the British rulers), they also built the country's infrastructure and the governance system. At the time of independence in 1948 from the Great Britain, 97% of export earnings of Sri Lanka came from exporting these three primary crops (65% came from tea alone) (Herath, 2004). Agricultural exports (tea, rubber and coconuts) continued to be the country's main source of export earnings until the late 1970s, when Sri Lanka moved from a 'closed economy' to an 'open economy' (via a constitutional change in 1977), promoting free trade (import and export). This paved the way for the rise of the apparel (garment) manufacturing industry in Sri Lanka, mainly due to low labour costs, the educated labour force (Sri Lanka's literacy rate of 91.2% is one of the highest amongst the developing countries), and an investment-friendly atmosphere.

The apparel industry has been Sri Lanka's largest gross export earner since 1986 (Dheerasinghe, 2003) and hence the leading industry sub-sector (Weeraratne, 2004), with share of around 40% of Sri Lanka's total export earnings (Satharasinghe, 2015) (see Table 1.1 for details). Therefore the apparel industry plays a major role in the development of the country. Globalisation has significantly affected the textile and apparel industry much the same way as it has affected the other sectors (Stengg, 2001). There is a fierce competition among the Asian countries (India, Sri Lanka, Bangladesh, China, Indonesia etc.) in the apparel manufacturing sector, chiefly due to low wage rates in those countries (Stengg, 2001). The companies that are successful in the global market are the ones that are able to provide high quality products at improved productivity (e.g. better use of machine time, less rework). One such Sri Lankan apparel company that stands out like a beacon in the global market is the researcher's case study organisation (Chapter 5).

Table 1.1: Exports of Textile and Garments (Source: Satharasinghe, 2015)

Year	Value of garment exports	Total Exports	Percentage of Garment Exports to total exports
2010	359,113	974,387	36.9
2011	440,791	1,167,588	37.8
2012	482,212	1,166,610	41.3
2013	551,656	1,342,971	41.1
2014	611,350	1,447,116	42.2

1.4. KEY DRIVERS FOR THE RESEARCH

There were several drivers that motivated the researcher to undertake the research. These are explained as follows.

The Conceptual Overlap Between Zero Waste and Zero Defects

Nicholas (1998) stated that manufacturing a product (or designing a process) to stay at its standard or target value results in zero variability, which equates to zero defects and

therefore, waste avoidance due to poor quality such as product recalls (unsatisfactory or defective product functionality), rework, and scrap. However, it is important to note that waste can manifest in several forms. Seven waste categories are mentioned in the literature: overproduction, waiting, unnecessary transport, over processing, unnecessary inventory, unnecessary movement, and defects (Hines & Rich, 1997; Ohno, 1988). For the purpose of this study, the researcher considers ‘zero defects’ and other waste categories separately. According to Nicholas, Taguchi’s RPD approach and Lean manufacturing are waste reduction approaches having some parallels to one another. Similar sentiments have been expressed by Wheeler (2010). However, Taguchi’s RPD approach has not been viewed as a strong component of Lean, even though both methods originated in Japan, a society that does not tolerate waste (Bhasin & Burcher, 2006; Holweg, 2007; Liker, 2004)³. At philosophical level, both Lean and Taguchi’s RPD approach (more technically, Taguchi’s Quality Philosophy) can be viewed as waste/loss reduction approaches. Lean views waste as a result of inefficiency in production (which needs to be eliminated). Taguchi’s RPD approach views waste as a by-product of failing to produce a product (or design a process) that is robust against the variability of the environmental factors (noise) that affect the product (or process), whilst in production or in use. Both Lean and Taguchi’s RPD approach are based on the premise that waste is undesirable. In Chapter 3 (see section 3.4.2) the researcher shows that Taguchi’s RPD approach is the vehicle within which Taguchi’s Quality Philosophy is brought into fruition.

Benefits to Academia and Practitioners

Lean manufacturing is a well understood manufacturing approach. However, the researcher’s study is the first serious attempt that looks at how Taguchi’s Quality Philosophy can be integrated in a Lean manufacturing environment to improve manufacturing outcomes (the boundaries/limitations of the research are covered in section 1.8). The study looks at the nexus between Taguchi’s RPD approach and Lean at theoretical (conceptual) level as well as practical level (actual application). Therefore the study attempts to make a valuable theoretical and practical contribution to the

³ Japan has a large population relative to its resources and landmass and optimum use of scarce sources has always being their forte.

discipline of operations management. Equally importantly, the study identifies several future research directions (section 9.4.2) for the academia.

The research could also be beneficial for Lean practitioners (particularly those who practise Lean manufacturing in a manufacturing environment similar to the one covered in this research) because it attempts to prescribe a practically useful set of recommendations to Lean apparel manufacturing organisations to increase the uptake of Taguchi methods to improve their operational performance (see section 8.3).

Benefits to Developing Countries

Apparel manufacturing is a very important sector in developing countries. This research has the potential to bring improvements to productivity in such countries. Since the research looks at improving the manufacturing outcomes in an apparel production setting in a developing country, the study could be more beneficial to developing countries that produce apparel. The study has the potential to benefit developed countries also if a similar study could be replicated in developed countries to test the same hypotheses that the researcher tested.

1.5. RESEARCH QUESTIONS

Given the background provided in the preceding sections, the overarching research question of the study is:

Does Taguchi's RPD approach (Taguchi's Quality Philosophy and the DoE methodology prescribed by Taguchi) appear to be a complimentary approach in a mature Lean apparel manufacturing environment to enhance Manufacturing Process Outcomes?

The overall hypothesis that is associated with the above research question is that, given the apparel manufacturing context, *"Taguchi's robust parameter design approach can complement Lean"*.

The specific research questions that stem from the overall research question are as follows. The reader should note that a stronger justification of these research questions

is provided towards the end of Chapter 3 (section 3.6), the second of the two literature review chapters.

The first research question is based on the seemingly complementary nature of Taguchi's Quality Philosophy (the building block of Taguchi's robust parameter design approach) and Lean, in that the former is aimed at reducing loss/waste and the latter is a management system that primarily aims at improving operational performance by reducing waste.

RQ1 How does Taguchi's Quality Philosophy theoretically relate to Lean, in improving the operational performance?

Answering RQ1 requires positing a theoretical framework within which Taguchi's Quality Philosophy relates to Lean to explain manufacturing process outcomes. The next step would be to test the theory within the boundaries defined by the researcher. This leads to the second research question.

RQ2 What is the acceptance of Taguchi's Quality Philosophy by the practitioners of Lean philosophy in the apparel industry?

If Taguchi's Quality Philosophy is related to Lean and if it is accepted as a viable paradigm by Lean practitioners in the apparel industry, then it is possible to examine how Taguchi methods work in Lean, given the boundaries defined by the researcher. This leads to third and fourth research questions.

RQ3 What are the statistical and operational merits and demerits (if any) of using Taguchi methods over conventional robust design experimental methods in solving important quality problems in apparel manufacturing?

RQ4 What drivers and what restraints do apply when Taguchi methods are actually being introduced in a mature Lean environment in the apparel industry?

1.6. AIM AND OBJECTIVES

Given the research questions (section 1.5), the aims and objectives of the research are as follows.

1.6.1. Research Aim

The overall aim of the study is to study the applicability of Taguchi's RPD approach (the quality philosophy and DoE methods prescribed by Taguchi) in a mature Lean manufacturing environment in apparel production.

1.6.2. Research Objectives

The specific research objectives of the study are as follows:

1. To formulate and statistically test a theory that predicts and explains how *Taguchi's Quality Philosophy* and *Lean* management jointly contribute towards improving the operational performance in a mature Lean apparel manufacturing environment.
2. To assess the suitability of Taguchi methods on statistical grounds as well as practical grounds to handle a substantial waste reduction problem faced by a mature Lean apparel manufacturer and compare these techniques with traditional DoE techniques in the setting studied.
3. To identify and describe the drivers and restraints associated with attempting to integrate Taguchi's RPD approach in a mature Lean organisation in apparel manufacturing.

1.6.3. General Research Objective

The general objective of the study is to formulate a practically useful set of recommendations that enable manufacturing organisations to increase the uptake of Taguchi methods for improving their operational performance.

1.7. METHODOLOGY OVERVIEW

The methodology used by the researcher to answer the research questions and thereby achieve the research objectives, could be summarised as follows.

- The first research question (RQ1), which relates to positing the theoretical relationship between Taguchi's Quality Philosophy, Lean, Continuous Improvement and Manufacturing Outcomes, was answered by developing a theoretical model through a comprehensive literature review.
- The second research question (RQ2), which relates to finding the acceptance of Taguchi's Quality Philosophy by Lean practitioners, was answered by testing the posited theoretical model using data (n = 318 usable responses) collected from respondents working in 31 factories belonging to the case study organisation, using a 40-item questionnaire developed by the researcher. The researcher used *Structural Equation Modeling* (covariance method) to test her posited theoretical model.
- The third research question (RQ3), which relates to finding the statistical and operational merits and demerits of Taguchi's prescribed DoE methods, was answered by the researcher by engaging herself with Lean practitioners in one of the factories belonging to the case study organisation, to solve a critical-to-quality problem using RPD methodologies; the DoE method prescribed by Taguchi as well as a key alternative DoE method prescribed by statisticians (detailed literature in Chapter 3) were put into test.
- The fourth research question (RQ4), which relates to identifying the drivers and restraints of organisational change (implementing Taguchi methods routinely, as part of the organisational culture), was answered using qualitative data collected by the researcher whilst she was conducting the experiments and engaging herself with Lean practitioners at the aforesaid factory. The researcher used "Lewin's Force Field Analysis" (see section 5.7.1 for an introduction to Lewin's Force Field Analysis) as the theoretical platform to explain the organisational change dynamics. The researcher considers the fieldwork done in connection with the third and fourth research questions as the most intrinsically rewarding part of her study. The researcher used the ethnographic approach to engage with the practitioners (particularly the frontline workers) to collect rich qualitative data during this phase of the study.

As it would become evident to the reader, the researcher uses multiple data sources and multiple methods to achieve her research objectives (triangulation), in keeping with the traditions of post-positivistic research (see section 4.2 in Chapter 4 for details).

1.8. LIMITATIONS AND DELIMITATIONS OF THE STUDY

A theoretical contribution becomes useful when the boundaries (delimitations) within which the study was conducted and uncontrollable factors that affected the scope of the study (limitations) are explicitly stated (Corley & Gioia, 2011; Whetten, 1989). As the study was the first of its kind that seriously looks at the relationship between Taguchi's RPD approach and Lean manufacturing, the researcher attempted to increase the breadth of the study at the expense of the depth of the study. This results in the following limitations and delimitations.

- The empirical model developed by the researcher does not include potential moderating factors such as the organisational culture, size, country etc. (these were deliberately held constant by limiting the study to factories in one country belonging to the same organisation). Moderating factors would have either enhanced or hindered the application of Taguchi's Quality Philosophy in a Lean context.
- The empirical model was tested based on cross-sectional data collected from respondents using a survey questionnaire. While such studies are very common in operations management (also in social science in general) theory testing, limitations such studies pose on internal validity (that is the ability to eliminate alternative causes for the effect/s being studied) needs to be acknowledged (Bryman & Bell, 2015; Forza, 2002; Wacker, 1998). In particular, the study *does not* look at whether an uptake of Taguchi's RPD approach actually increases the outcomes of the case study organisation.
- The entire study was conducted in an apparel manufacturing environment. The findings may not be generalisable across Lean environments other than apparel manufacturing. This is an issue on "external validity" (Bryman & Bell, 2015; Campbell, Stanley, & Gage, 1963).

- The case study that was used to answer the third and fourth research questions was a single case study design (the data were drawn from one organisation). This limits the external validity (generalisability) of the findings (Yin, 2014).

1.9. THE STRUCTURE OF THE THESIS

The remainder of this thesis has been structured as follows.

Chapter 2 begins with a review of the literature on Lean, in relation to manufacturing systems, its applications, associated issues, and limitations. This chapter also covers the relevant literature on Statistical Thinking, Continuous Improvement (Continuous Improvement is inherent in Lean thinking), Six Sigma (a quality and systems improvement approach), and Lean Six Sigma (a variant of Six Sigma). The chapter concludes with the key points carried forward to the next chapter (Chapter 3) to frame the research questions.

Chapter 3 continues the literature review by covering the relevant product quality improvement literature that involves experimentation. More specifically, Chapter 3 provides the basic literature on the traditional DoE approach (as a background to understand and critically review the literature on RPD approaches), the literature on Taguchi's RPD approach (much of Chapter 3 covers this subject area) as well as the major alternative approach advanced by statisticians—the “response surface alternative to Taguchi's RPD approach” (Khuri & Mukhopadhyay, 2010). Towards the end of the chapter (section 3.6), the researcher highlights the knowledge gaps and the corresponding research questions of the study.

Chapter 4 covers part of the methodology. This chapter begins with a review of research paradigms available and justification of the particular paradigm chosen by the researcher. This is followed by theoretical model development, through an extensive literature review. The model explains the relationships between Taguchi's Quality Philosophy, the Lean Manufacturing System, and the operational outcomes, through the mediating effect of Continuous Improvement. Thereafter, the chapter describes the development of the survey questionnaire (through the literature) to collect data to test the theoretical model (see Appendix A for the questionnaire). This is followed by a description of how the sample was selected to administer the survey among Lean

apparel manufacturing factories in Sri Lanka (all factories belonged to the case study organisation to ensure that the organisational context remains *Lean apparel manufacturing*) as well as how the data were actually collected and coded for data analysis. Furthermore, Chapter 4 explains the methods and strategies that were used to assure the *methodological rigour*, such as assuring reliability, validity, and lack of method bias. *In essence, this chapter answers the first research question (RQ1)*. Parts of this chapter have been published in two conference proceedings. An overview of the study was presented at the 2012 World Business Capability Congress (Gamage, Jayamaha, & Grigg, 2012) while the theoretical model development was presented at the 11th ANZAM Operations, Supply Chain and Services Management Symposium (Gamage, Jayamaha, Grigg, & Nanayakkara, 2013).

Chapter 5 covers the remaining portion of the methodology. This chapter begins by reviewing the relevant literature on the case study methodology. The apparel manufacturing factory (based in Kandy, Sri Lanka) in which the case study was conducted is introduced immediately afterwards (the researcher collected experimental data as well as qualitative data at this factory). This is followed by the data collection methods and strategies. *Quantitative data* were collected to conduct statistical analysis, among other things, to identify robust parameter settings. *Qualitative data* were collected to identify the operational merits and demerits of using Taguchi methods over conventional DoE methods on RPD, as well as to understand the forces (drivers and restraints) that affect implementation of Taguchi methods.

Chapter 6 begins with the demographic information of the data collected through the questionnaire. Since the theoretical model contains latent variables, concepts related to latent variables are covered in this chapter, prior to introducing the statistical concepts on Structural Equation Modelling (SEM) and related concepts. This is followed by the presentation of the results on the validity and reliability of the measurement scales used in testing the theoretical model, based on the survey data. Upon completion of model testing, within Chapter 6, the researcher interprets the results from a theoretical and practical perspective, through a *discussion* section. *In essence, this chapter answers the second research question (RQ2)*. Some sections of this chapter (theoretical model testing) have been published as a conference proceeding at the 12th ANZAM Operations, Supply Chain and Services Management Symposium (Gamage, Jayamaha,

Grigg, & Nanayakkara, 2014b). The paper won the best paper award at the conference (Appendix B).

Chapter 7 provides an analysis of the test results on Taguchi's RPD approach and the alternative DoE approach (a response surface alternative to Taguchi's RPD approach). This is followed by the presentation of the optimum parameter settings (the optimal level to be set for each controllable factor) to minimise variation to improve product quality. Thereafter the researcher provides a comparative analysis (a discussion) between the two methods from a statistical and operational perspective, based on her experience in solving the quality improvement problem. *In essence, this chapter answers the third research question (RQ3)*. Some parts of this chapter (the experimental design) have been published in form of a conference proceeding at the 2014 IEEE International Conference on Industrial Engineering and Engineering Management (Gamage, Jayamaha, Grigg, & Nanayakkara, 2014a).

Chapter 8 uses "Force Field Analysis" (Lewin, 1951) as an analytical tool to identify the drivers and restraints that govern organisational change, when Taguchi methods are actually being introduced in a mature Lean apparel manufacturing environment. *In effect, this chapter answers the final research question (RQ 4)*. The chapter discusses organisational change management issues, based on the findings (qualitative) of the researcher's case study. This achieves the general research objective of the study.

Chapter 9, the final chapter covers the summary of the findings in relation to the research questions and research objectives. Finally, the limitations of the study and directions for future research work are presented in this concluding chapter, along with the researcher's final thoughts.

Figure 1.2 depicts the links between the research questions, research objectives, findings, and the thesis chapters.

AGENDA

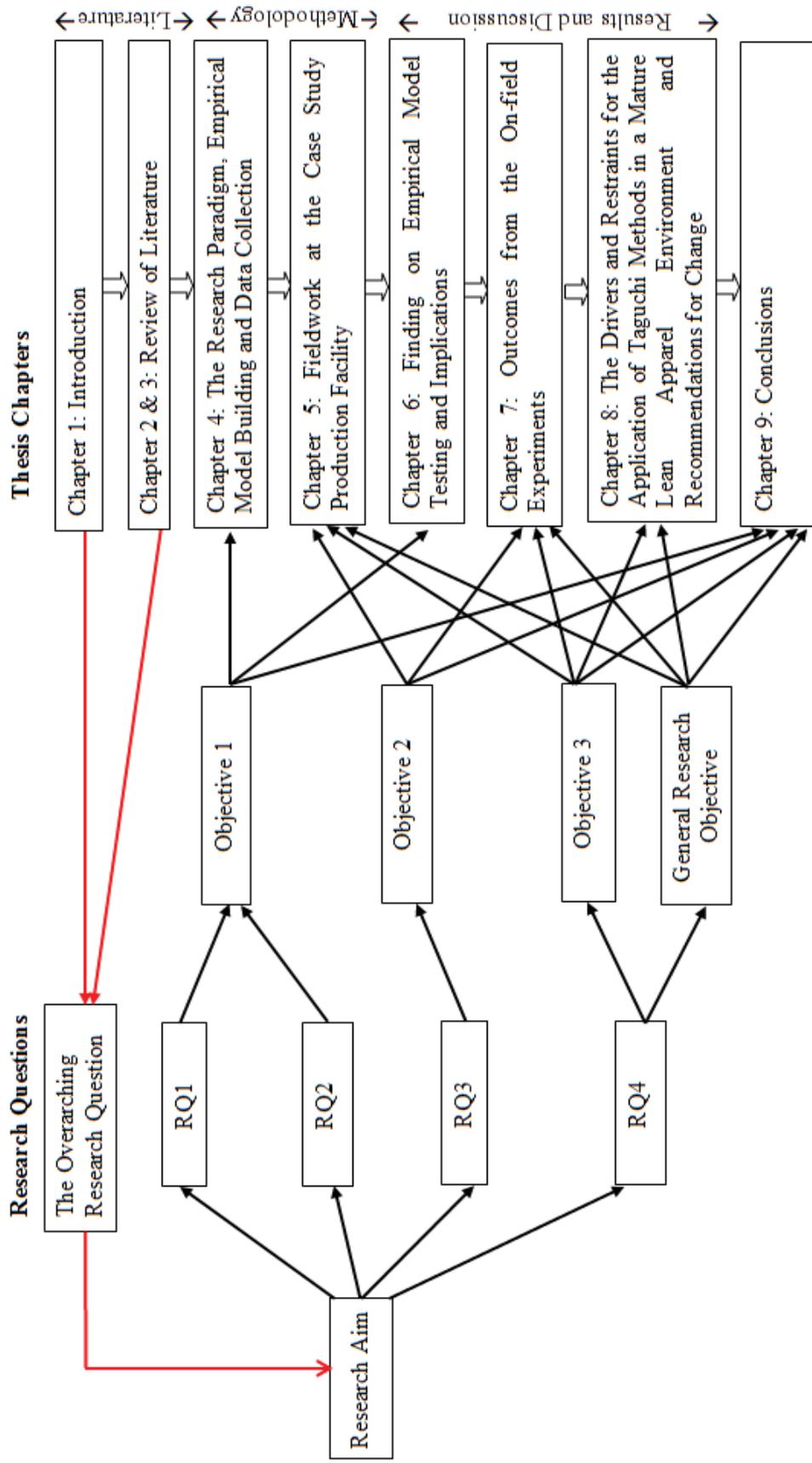


Figure 1.2: The links between the research questions, research objectives, findings and the thesis chapters

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CHAPTER 2

LEAN MANUFACTURING SYSTEMS AND RELATED CONCEPTS

*“Some books are to be tasted, others to be swallowed,
and a few to be chewed and digested”*

—Francis Bacon

2.1. INTRODUCTION

This is the first of two chapters that covers the literature relevant to the study. Since the overall aim of this study is to understand the applicability of Taguchi’s robust parameter design RPD approach in a mature Lean apparel manufacturing environment, considerable portion of this chapter is dedicated to reviewing the literature on Lean Manufacturing Systems (the context within which RPD is applied) and two inter related concepts statistical thinking and Continuous Improvement (CI). Statistical thinking concerns understanding variation, which is also an important aspect in Taguchi’s RPD approach covered in the next chapter.

The subject domains (conceptual space) that underpin the study are shown in Figure 2.1. As depicted in Figure 2.1, the study underpins several overlapping concepts. The reader should note that mapping each subject domain shown in Figure 2.1 through a scoping review is beyond the scope of the literature review. Therefore Figure 2.1 does not attempt to quantify the degree of overlap among the subject domains.

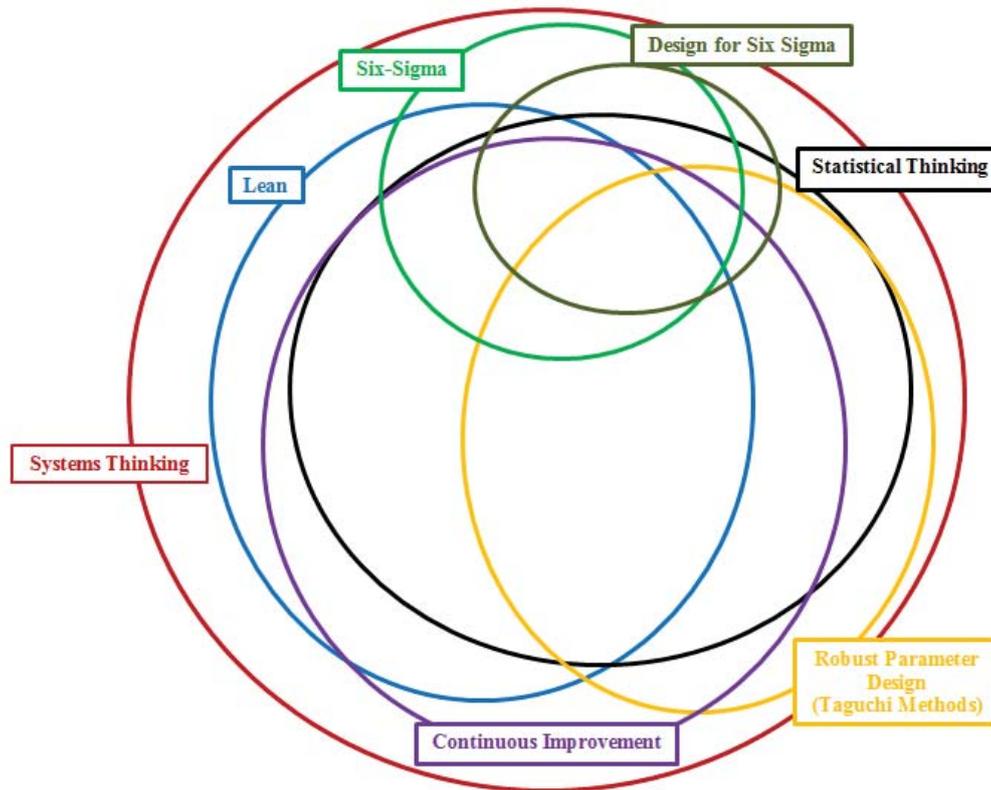


Figure 2.1: The overlapping concepts and subject domains that underpin the research

All the sections covered in this chapter relate to processes that take place within an organisation. As such, all subject domains covered in this chapter can be viewed as subsets of systems thinking, in an organisational context. Jackson (2003) argues that systems thinking is a scientific view point that helps one to understand the functioning of a complex whole—be it a naturally existing physical system, a biological system, a designed system, an abstract system, a social system, or a set of organised human activity to achieve a common goal—through its constituent parts as well as the *interactions* between the parts.

Section 2.2 covers the concept “Lean” or more precisely, the concept *Lean Manufacturing System*, the obvious main subsystem of a Lean manufacturing organisation. CI, is an integral part of Lean, refers to improving the processes and their outcomes on an ongoing basis. Almost invariably, CI decisions in organisations are based on the measurement of product or process performance, which subsumes a certain element of uncertainty. This uncertainty resides in the subject domain of statistical thinking. Consequently a wide range of subject domains that come under the purview of CI and statistical thinking are covered in section 2.3. These include *Six Sigma* (section

2.3.5) and *Lean Six Sigma* (section 2.3.6). Finally, section 2.4 concludes the chapter with the key points that will be carried forward to the next chapter, in framing the research questions.

2.2. A LEAN MANUFACTURING SYSTEM

A Lean Manufacturing System is a subsystem of a manufacturing organisation (the primary system). In contemporary literature a Lean Manufacturing System is viewed as a socio-technical system engaged in creating value to the customers by eliminating waste and non-value adding activities from all activities of the value chain, not just activities within a factory (Jayamaha, Wagner, Grigg, Campbell-Allen, & Harvie, 2014; Shah & Ward, 2007). Much of the current thinking on Lean evolved from the work of the researchers (e.g. Hopp & Spearman, 2004; Liker, 2004; Monden, 1998; Womack & Jones, 2003) who examined the efficiency and the effectiveness of the production system at the Toyota Motor Corporation, Japan, commonly known as the Toyota Production System (TPS). Liker and Morgan (2006) assert that TPS is “a true systems approach which effectively integrates people, processes, and technology—one that must be adopted as a continuous, comprehensive, and coordinated effort for change and learning across the organisation”.

Taiichi Ohno (1912-1990), widely regarded as the father of the Toyota Production System, identified seven waste categories that need to be avoided in a Lean production system: overproduction, waiting, unnecessary transport, over processing, unnecessary inventory, unnecessary movement, and defects (Hines & Rich, 1997; Ohno, 1988). Each waste category is described in turn.

Overproduction: As the term implies, over production refers to producing goods in excess of what is required. Overproduction is regarded as the most severe form of waste because it causes significant disruptions to the smooth flow of goods—raw material, work in process (WIP) goods, and finished goods—resulting in serious productivity issues (e.g. inefficient utilisation of manufacturing resources) and product quality issues (e.g. deterioration of the functional performance due to storage) . Overproduction also ties up the working capital. ‘Pull’, the fourth principal of Lean (section 2.2.1), is meant to eliminate overproduction (Hines & Rich, 1997; Liker, 2004).

Waiting: Waiting refers to workers waiting for machines, equipment, waiting for the next step of processing. Waiting adds additional cost to end product. Heijunka or production levelling can be applied to minimise waiting in production processes (Liker, 2004).

Unnecessary transport: Unnecessary transport refers to moving WIP goods from one place to another in a process or moving parts or finished goods in or out from inventories (Liker, 2004). Unnecessary transportation consumes additional time and labour, which do not add value to end product (Liker, 2004).

Over processing: Over processing or inappropriate processing refers to taking unnecessary (or inappropriate) steps to make products of right quality. This typically happens when overly complex solutions are sought when simple procedures exist out there (Hines & Rich, 1997). Hines and Rich observe that over processing leads to other forms of waste (e.g. unnecessary transportation) as well as “lack of ownership” on the part of frontline workers. Unnecessary inventory: An unnecessary inventory can result from overproduction or keeping inventory items that are not required in production (e.g. excessive storage of slow moving items) (Hines & Rich, 1997). Hines and Rich observe that problems (e.g. excessive lead time, increased space) can get hidden behind inventories, when unnecessary inventory exists.

Unnecessary movement: Unnecessary movement refers to any motions initiated by employees during the work (e.g. stretching, bending, picking) that could be avoided through ergonomically designed layout. Unnecessary movement do not add value to the product. Unnecessary movement typically results from an inefficient plant layout, which also contributes to unnecessary transportation and poor product quality (Liker, 2004).

Defects: Producing defective parts or products causes repair, rework, inspection, all of which mean waste of resources that could have been avoided through superior design and conformance quality (Liker, 2004).

2.2.1. The Constituents of Lean Thinking

According to the literature, one of the major obstacles of understanding Lean is the absence of a common definition for it (Hines et al., 2004; Shah & Ward, 2007). Womack and Jones (2003) defined a Lean as a system that operates on five principles: *specifying the value, identifying the entire value stream, creating flow, pull, and pursuing perfection*. These five principles have found to be useful in extending Lean beyond automotive production within and outside manufacturing (Haque & James-moore, 2004; Hines, Found, Griffiths, & Harrison, 2008). The five components are described in turn.

Step 1: Specifying the Value

Being an evolving concept, the current understanding of Lean is that it is no longer confined to shop floor activities such as kaizen (CI) activities to reduce waste (Hines et al., 2004). The current thinking is that (from a firm's point of view) ultimately, it is the customer who defines what waste is, through the "customer value proposition". This is consistent with Womack and Jones's "Lean consumption" proposition described in the next section (Hines et al., 2008; Hines et al., 2004).

Identifying the customers and specifying customer value (i.e. defining in which way the customer value can be created and enhanced) are considered to be the starting point (the first principle) of Lean thinking (Womack & Jones, 2003). Customers get *value* when the producer is able to *design and produce* products (and services) *that meet or exceed customer expectations at the least possible cost*. Until very recently, much of the academic and practitioner focus has been on the efficiency aspects of Lean only, in particular reducing all forms of waste (Haque & James-moore, 2004; Schulze & Störmer, 2012). While production efficiency is an important aspect in manufacturing; efficient processes alone do not explain why the products produced by these processes exceed customer expectations—that is, why the production system is effective (e.g. producing products that provide greater performance, greater reliability, greater durability etc. are product dimensions that reflect the effectiveness rather than the efficiency of a production system).

There is a general understanding that value creation means cost reduction through eliminating waste. Hines, Holweg, and Rich (2004) showed two different avenues that

create value: reduction of internal waste and addition of features or services valued by the customers at little or no additional cost. Prior to examining the argument advanced by Hines et al., it is important to define *customer value*. In marketing and strategic management, customer value is defined as the totality of customer's perceived benefits of acquiring and using the product or service (i.e. customer-perceived value of product or service) less the cost of creating those benefits (Armstrong & Kotler, 2015; Parasuraman, 1997; Slater & Narver, 1994).

Figure 2.2 (copied from Hines et al., 2004) shows the two avenues through which customer value is created. The 45° slope dash line provides the reference (datum): any point in this line (e.g. A) represents zero customer value because customer perceived value of product (or service) equates the cost of product (or service). Any point above the reference line (e.g. B, C) shows positive customer value while any point below the reference line shows negative customer value (Hines et al., 2004). Path A → B shows the typical value creation occurrence in a Lean organisation, namely provide the customer perceived value at a reduced cost by eliminating internal waste (most of the cost could be reduced by eliminating internal waste the more customer value is being created). Path B → C shows an instance of developing additional customer value at the same cost. In the literature it is argued that a Lean organisation can create this additional value by building superior products (or services) utilising the time that the organisation would have otherwise spent on non-value adding activities (Carreira, 2005; Hendry, 1998).

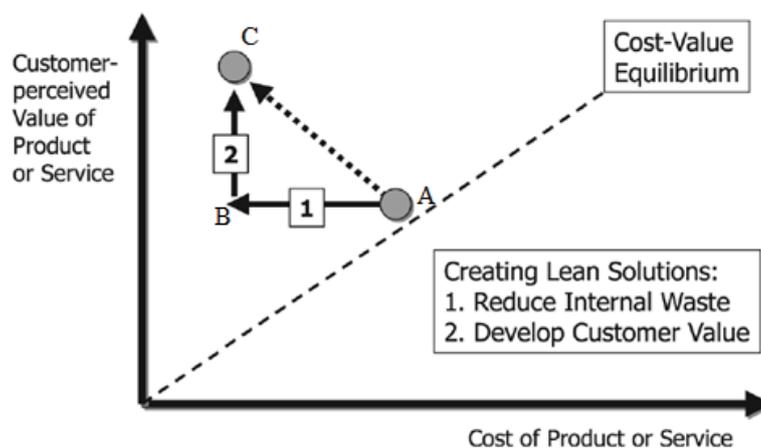


Figure 2.2: Relation of value, cost and waste (Source: Hines et al., 2004)

Haksever, Chaganti, and Cook (2004) proposed a model of value creation based on three dimensions: financial, nonfinancial, and time. The importance of this study is that the authors discuss value creation from the perspective of all key stakeholders, not just from the perspective of customers. Customer value creation (or destroying customer value) is reviewed first. Haksever et al. show that the financial value is created for the customer when the product is supplied at superior quality at a competitive price (e.g. a product that does not require frequent repairs and/or maintenance). Nonfinancial customer value according to the authors is created when the customer gets any tangible or intangible benefit by acquiring and using the product, given that the product performs as claimed (e.g. the benefits a dishwasher provides over manual washing). As regards *time value* associated with acquiring and using a product, the authors assert that customer value can be created primarily in three ways: time savings gained by the customer, product durability (functioning of the product over a long span of time), and delivery (providing the product when the customer needs it every time). According to the authors, when the product fails to provide value along any of the dimensions (financial, nonfinancial or time), the value is said to be destroyed—for example, when the customer has to repair or return a defective product, when maintaining the product becomes expensive to the customer, and when the product usage becomes hazardous to the customer (and the environment).

Through examples Haksever et al., (2004) show how value creation brings financial benefits to the shareholders such as profit and stability, nonfinancial benefits such as prestige, goodwill associated with the valuation of the assets, and time benefits such as long term stability, scope for new product development and new technology. Similar examples on time benefits associated with value creation have been provided by the authors on value creation for employees, suppliers and the wider society. This is important because Lean literature often tends to downplay the value created to these stakeholders.

Step 2: Identifying the Entire Value Stream

After specifying the value in the first step, identifying the value stream is the second principle in Lean thinking (Womack & Jones, 2003). Value stream is the set of activities that are required to bring value to a customer from the specific product (or

service). Womack and Jones (2003) identify three key tasks in connection with a value stream: the problem-solving task, the information management task, and the physical transformation task. Value stream is mapping the activities and information flows of the whole value chain starting from the stage of raw material receipt from supplier through to the delivery of the finished goods to the customers. The literature on value stream mapping identify three different types of activities: value adding activities (activities that add value to the product), non-value added activities (activities that do not add value to the product) that can be removed, and non-value added but needed activities; (activities that cannot be removed with the existing technologies and production assets) (Jones & Womack, 2002; Monden, 1998; Womack & Jones, 2003).

In the value stream mapping step, organisations map their current state of the system, which can be the whole organisation or a department (or any other system that is under review), as well as the future state of the system based on the strategic goals pursued. The organisation then needs to take relevant action to improve the process continuously to fill the gap between the current state and the future state (as mapped); these actions result in the removal or at least reduction of waste.

Step 3: Creating Flow

The third principle in Lean thinking according to Womack and Jones (2003) is to make a flow of the value added activities that remain in the system (i.e. after removing the non-value added activities from the previous step of the value stream). They assert that making the flow requires moving away from the so called “*departmentalised thinking*” or “batch-and-queue” style flow, which add costs in the form of over production, waiting and so on (i.e. waste). The literature on TPS (e.g. Jones & Womack, 2002; Liker, 2004; Monden, 2011; Vyas, 2011) demonstrate how flow of value creating activities for a specific product removes the barriers among departments and batches to shift to continuous flow, which increases production, reduces errors, scrap, overproduction and queuing. If the departments and activities can be redefined to make a positive contribution to value creation and engaged the workforces for real needs will pave the way of employees’ interest to make value flow.

Step 4: Pull

Letting the customer pull the product, where signal to produce (work release) comes from the downstream customer, is the fourth principle in Lean thinking (Womack & Jones, 2003). Conventional production on the other hand relies on “push production” that relies on building large inventories (Mao, Yang, & Xu, 2014; Richardson & Malone, 2012; Womack & Jones, 2003). This is to avoid or reduce additional costs that would otherwise accrue (in push product) as a result of large inventories and unsold product that would be returned to the producer (or scrapped) for not being able to sell. Manufacturing literature support the notion that pull-production provides superior benefits (over push production) to the manufacture when there is demand certainty and slow product introduction frequency (Bruce, Daly, & Towers, 2004; Pullan et al., 2011; Richardson & Malone, 2012).

Step 5: Pursuing Perfection

Perfection is the final principle in Lean thinking, where process improvement continuous up until all activities (to the extent possible) become value added (Womack & Jones, 2003). Transparency, where issues (waste/non-value adding activities) are displayed for everyone to see, which is identified as the most important requirement for the perfection, as this facilitates discovering better ways to create value and to provide timely feedback on the improvements made by employees (Womack & Jones, 2003). Perfection also facilitates the flow (step 3) and the pull (step 4), according to Womack and Jones.

In the literature, there are two types of process improvements associated with Lean: *kaikaku* (radical improvements) and *kaizen* (gradual improvement). In *kaizen*, there is no end to the process of improvement, which may be reducing effort, time, space, cost, and mistakes while trying to provide a product that the customer actually wants (Bhuiyan & Baghel, 2005; Rother & Shook, 2003; Singh & Singh, 2012).

A number of researchers show the importance of adopting an organisation’s own version of Lean production by merging its existing socio-technical system with Lean thinking, rather than attempting to blindly copy the TPS outright (Eklund & Berglund, 2007; Seppälä & Klemola, 2004). Number of organisations in the Scandinavian

countries have introduced their own version of Lean (e.g. Scania Production System, BT Production System); in general, these tailor-made Lean systems have shown better performance over Lean systems that have been copied from the TPS (Eklund & Berglund, 2007; Friel, 2005). The reader may note that the Lean manufacturing organisation from which the data were collected for this research has also devised its own Lean version, which is called the “X Operating System (XOS)” (X is a pseudonym given by the researcher to prevent the identification of the organisation).

2.2.2. Lean Consumption

In a subsequent version, Womack and Jones (2005b) extended their five principles of Lean to encompass the broader process of “consumption”. They named their new/improved proposition as “Lean consumption”. The main reason for this new approach was to take into account the deterioration (or otherwise) of consumer’s experiences with product when they use it (Womack & Jones, 2005b). Womack and Jones argued that customers are indifferent to factory records such as statistical process control (SPC) records showing high process capability/conformance (i.e. products within specifications nearly 100% of the time) or records showing how scrap was minimised. This is because (according to Womack and Jones) even though the products are mass produced, they reach the customer as a single product for each customer and the only proof of product quality to the customer is its functionality (e.g. performance, reliability, durability etc.), once the product is in the customer’s hands.⁴ Conceptually, Lean consumption highlights the importance of developing quality products upfront (that is building quality in the design stage) while maintaining high production efficiency levels (e.g. high labour utilisation, low waste) as emphasised in traditional Lean manufacturing. The robust design approach is an established approach of building quality upfront, which is reviewed later in next chapter (Chapter 3).

⁴ Garvin (1987) provided an 8-dimensional framework to evaluate the multi-faceted nature of product quality: performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality. Therefore it is difficult to provide a single dimension that captures the products functionality. According to Garvin, performance is the primary operating characteristic of the product. However, according to Garvin, dimensions such as the reliability, conformance, and durability also define a product’s functionality.

2.2.3. Operationalising Lean

It appears from the literature (e.g. Davy, White, Merritt, & Gritzmacher, 1992; Jayamaha et al., 2014; Jayaram et al., 2010; Liker, 2004; Liker & Morgan, 2006; Shah & Ward, 2007) that Lean production does not have a universal operational definition—that is, a set of concepts/constructs that predict and explain the outcomes achieved by a Lean production system (Davy et al., 1992; Jayaram et al., 2010). Some prior studies are reviewed as follows.

Based on 20 years of experience at the Toyota, Liker (2004) identified 14 principles (measures) of the TPS: taking a long term perspective on management decisions (P1), creating continuous flow (P2), the pull system (P3), levelling out the workload (P4), creating a culture of stopping production to fix the problem (P5), standardisation of tasks to facilitate CI (P6), use of visual controls (P7), using reliable and validated technology (P8), growing leaders within the organisation who thrive on problem solving (P9), people and team development (P10), partnership/supplier development (P11), go to the source to thoroughly understand the problem/s (P12), consensus decision making (P13), and becoming a learning organisation (P14). Furthermore, Liker (2006) viewed Lean/TPS as a complex inter-wound system consisting of four elements: philosophy, process, people, and problem solving. The four elements were represented as the “4P model” in which 14 principles (measures) have been assigned to the respective element: P1 to philosophy, P2 through to P8 to process, P9 through to P11 to people, and P12 through to P14 to problem solving (Liker, 2004; Liker & Morgan, 2006).

Through and exhaustive review of prior literature on measures of Lean production/TPS and content validation, followed by confirmatory factor analysis, Shah and Ward (2007) showed that a Lean production system can be resolved into 10 components: supplier feedback (C1), just-in-time delivery (C2), supplier development (C3), customer involvement (C4), pull system (C5), flow (C6), setup time reduction (C7), total productive/preventive maintenance (C8), statistical process control (C9), and employee involvement (C10).

It is important to note that Toyota Motor Corporation (TMC) themselves have defined (in 2001) how they go about in achieving their outcomes across their whole value chain; they called this is the “Toyota Way” (TMC, 2001, 2006). According to Toyota, the

Toyota Way (TW) consists of two fundamental/overarching concepts: “*Respect for People*” and “*CI*” (Emiliani, 2006; TMC, 2001). According to Toyota, respect for people in the TW means engaging in two processes: respecting people and partners, and teamwork. Likewise, CI in the TW means (according to Toyota) engaging in three processes: taking a long-term orientation towards problem solving and getting results (which they termed as “challenge”), kaizen (incremental improvement), and getting to where “real action takes place” to solve problems (which they termed “Genchi Genbutsu”) (Jayamaha et al., 2014; TMC, 2001). Many of the elements of Lean/TPS that the other researchers have elicited are subsumed in the two fundamental/overarching concepts of the TW (Jayamaha et al., 2014; Rother, 2010).

Using data collected from a large sample of Toyota employees ($n = 2613$) across 26 countries Jayamaha et al. (2014) validated the TW. After redefining the TW constructs as People Development (instead of “Respect for People”, the name given by Toyota) and Process Improvement (instead of “CI”, the name given by Toyota), they tested the overall hypothesis that Process Improvement is driven by People Development to achieve the TW outcomes. Using the resource based view on competitive advantage (Barney, 1991), Jayamaha et al. argued that People Development reflects Toyota’s intangible resource which enables Toyota to gain the competitive advantage by being able to effect process improvement (Toyota’s tangible resource) to achieve TW outcomes (Barney, 1991). The results yielded by their Structural Equation Model implied that although People Development has no direct effect on TW outcomes, People Development nonetheless has a very strong indirect effect on the TW outcomes via the mediating variable Process Improvement. They interpreted this result to mean that for a complete implementation of Lean, People Development should be aimed at effecting Process Improvement (kaizen, long-term thinking on improvement, and Genchi Genbutsu).

2.2.4. Product Development in Lean

While CI is the backbone of Lean, CI literature does not seem to explain how customer value can be built into the products (see Figure 2.2 included in a previous section), particularly in environments characterised by short product lifecycles. For example, in the electronic industry, the product manufacturing cycle time is often shorter than the

actual product development (PD) time, which consists of rework, several product development iterations (due to number of causes), implementation, synchronisation and so on (Bauch, 2004; Mathrani, Mathrani, & Liu, 2011), resulting in relatively long cycle times and risk. To compound matters the duration of the PD process also includes the products' "time to market". Therefore protracting the PD time has the potential to radically minimise the time to market, which in turn could affect a firm's competitive success (Brown & Eisenhardt, 1995; Gautam & Singh, 2008). More recent literature on Lean (e.g. Hoppmann, Rebentisch, Dombrowski, & Zahn, 2011; Johansson & Sundin, 2014; Khan, Al-Ashaab, Shehab, Haque, Ewers, Sorli, & Sopolana, 2013; Saunders, Gao, & Shah, 2014; Schulze & Störmer, 2012) attempt to address how new product development (NPD) can exist in a Lean environment.

Designing and delivering products using Lean thinking, sometimes referred to as Lean PD and other equivalent names such as Lean product introduction and Lean product lifecycle management is a relatively new concept that is receiving the attention of the scholars (Haque & James-moore, 2004; Khan et al., 2013; Schulze & Störmer, 2012). Most of the early literature on Lean PD (e.g. Liker & Morgan, 2006; Walton, 1999) appear to have focused on applying TPS/Lean principles and/or Lean tools in PD—for example, the 14 TPS principles of Liker (2004) in Liker and Morgan, (2006), rather than attempting to understand the conceptual domain of Lean PD.

Haque and James-Moore (2004) conducted two case studies in two different new product introduction (NPI) organisations: Rolls-Royce (a leading prime mover provider for air, sea and land applications) and Weston Aerospace Limited (a medium sized aerospace company). Haque and James-Moore showed how both the companies successfully applied Lean for NPI processes. In particular the researchers found that Lean facilitates the high level of coordination and integration required among various parties involved in PD. They also showed that Lean is not solely concerned with creating value through production and supply chain efficiency but also with product development to enhance a positive customer experience in using the product; this aspect has also been emphasised in Womack and Jones' Lean consumption proposition (section 2.2.2).

While there seems to be no consensus on the constructs on Lean PD, most of the recent studies show several common drivers and enablers of Lean PD: set-based engineering

(generating a large number of design solutions in the initial stages of PD and gradually reducing sets of alternatives), customer value proposition (e.g. value stream mapping), technical leadership, a learning culture, and kaizen (Johansson & Sundin, 2014; Khan et al., 2013; Schulze & Störmer, 2012). However, researchers have attempted to identify the barriers to PD in a Lean environment. For example, Gautam and Singh (2008) argued that more attention should be placed on customer perceived value during the PD process. León and Farris (2011) argued that Lean PD research lacks the application of the “pull” concept, the most salient feature of Lean and that there is scope to utilise this concept in the generation and assimilation of information in the value chain (e.g. to generate and transmit information from upstream to the downstream only if and when required).

Krishnan and Ulrich (2001) as well as Johansson and Sundin (2014) argue that the models employed in PD research are not driven by industry practice and that the application of scientific principles in PD are generally lacking. For example, Johansson and Sundin contend that because Lean begins with identifying the customers and defining the value, Lean PD should focus on using scientific tools such as the quality function deployment (QFD) to match product’s technical/engineering characteristics with customer requirements (e.g. engineering the specific functionality into the product as envisaged by the customer). On the same token one can surmise why design of experiments (including the robust design approach) has not been a key focus in published literature on PD in general and Lean PD in particular. It can be argued that the research described in this thesis focuses on the cutting-edge of research on Lean and the scientific principles of quality management.

2.2.5. Application of Lean in the Apparel Industry

Lean thinking has been applied in a wide variety of manufacturing and service sectors all around the world. The apparel industry is no exception. Bruce, Daly, and Towers (2004) illustrated the application of related approaches Lean, agile, and leagility (leagility is a term used to mean a hybrid approach of Lean and agility) for textile and apparel companies. They observed that textile and apparel companies have to respond quickly to market changes because of shorter product life cycles, low predictability etc. Through conducting case studies they concluded that implementing a combination of

Lean and agile (leagility) is more effective in the textile and apparel industry than implementing Lean or agile alone.

Through interviews and three case studies Hodge et al., (2011) developed hierarchical Lean implementation model that specifies the Lean concepts (principles) and the associated tools and techniques for textile manufacturing in the United States. Their six-construct sequential model (from the bottom of the hierarchy to the top of the hierarchy) consists of *Policy Deployment* (Tools and Techniques: PDCA, change by consensus, catch ball, and A3) → *Visual Management* (Tools and Techniques: 5S, Andons, and TPM) → *CI* (Tools and Techniques: Rapid Improvement, Root Cause Analysis, and Mistake Proofing) → *Work Standardisation* (Tools and Techniques: Takt Time and Cycle Time, Job Element Sheets, and Work Sequencing) → *Just-In-Time* (Tools and Techniques: Kanban, Quick Changeover, and Supermarkets) → *Customer Satisfaction*. They also identified Value Stream Mapping as the general tool that can be used across all layers of the hierarchy.

There are also studies (Abernathy, Volpe, & Weil, 2006; Weil, 2006) on the application of Lean principles on inventory decision analysis in textile retailing. The main motivation for application of Lean in textile retailing seems to be reducing inventory carrying costs and mitigating the associated risks.

2.2.6. Humanistic and Other Criticisms Associated with Lean

A major criticism of Lean thinking is its lack of consideration on human aspects (i.e. taking a mechanistic stance on employees) (Hines et al., 2004). For example the focus in Lean can shift from designing jobs that motivate people to reduce cycle time, which is a mechanistic goal. However, Lean plants in Japan are designed to provide high quality products to the customer at the right time at the right price to satisfy the customer. Some critics of Lean (e.g. Conti & Warner, 1997) admit that customer value creation brought about by Lean is important for the stability of the company, pride, and job security of the employees, and therefore Lean has an indirect effect on employee satisfaction (Conti & Warner, 1997). These critics also appreciate that Lean makes the work place more organised, which in turn reduces worker frustration and fatigue the workers may otherwise experience in searching tools, assembly parts, and so on. Therefore, it can be argued that although Lean does not directly address employee

satisfaction, employees nonetheless indirectly benefit through Lean processes (Conti, Angelis, Cooper, Faragher, & Gill, 2006).

Another criticism of Lean is that although Lean approaches attempt to find ways of utilising the resources to increase the capacity and reduce the variability (which helps in reducing the cost of the product) they do not contribute towards increasing the perceived worthiness of the product substantially through superior product design (Hines et al., 2004). However it seems that this criticism is levelled at the traditional Lean concept but not the more contemporary Lean concepts such as Lean consumption and Lean PD.

Yet another criticism of Lean is that Lean does not fit well in low-volume, high variety manufacturing environments such as machine tool manufacturing and textile manufacturing. This is because high product variety (especially under lower volumes) challenges *pull production*—one of the most salient features of Lean manufacturing (Bruce et al., 2004; Pullan et al., 2011).

2.3. STATISTICAL THINKING AND CONTINUOUS IMPROVEMENT

Statistical literacy, reasoning, and thinking are fundamental to building knowledge (Ben-Zvi & Garfield, 2004). In Lean, the practitioner needs to understand the customer and the processes so as to improve the processes continuously to create value (Jayaram et al., 2010; Womack & Jones, 2003). In quality, the practitioner needs to understand the customer to build quality into products and services in the first place (quality in design); also, the practitioner needs to monitor their processes continuously to ensure that the processes and outcomes (e.g. product specifications) remain predictable (quality in conformance) (Antony, 2011; Juran, 1986). None of the above can be achieved by the practitioner without statistical thinking.

2.3.1. Introducing Statistical Thinking

The origin of statistical thinking probability dates back to the work of John Graunt in the mid fifteenth century; this work was published in 1662 in the book “Natural and Political Observations” (cited in Pfannkuch & Wild, 2004). In a very broad sense, statistical thinking is the thought processes followed by a statistically minded person

(e.g. a scientist, an engineer) when conducting empirical inquiries (Ben-Zvi & Garfield, 2004; Pfannkuch & Wild, 2004). Statisticians have attempted to operationalise statistical thinking. Understanding the omnipresent variation in data, which can come from the variability of the phenomenon being observed as well as the variability in collecting data (e.g. sampling, measurement devices, people who collect data) remain a common element in all operational definitions of statistical thinking (Ben-Zvi & Garfield, 2004; Pfannkuch & Wild, 2004; Snee, 1990).

In the area of quality, the credit of applying statistical thinking goes to Walter A. Shewhart (1891-1967) (Shewhart & Deming, 1967; Snee, 1990). Shewhart's early work (at Bell Telephone laboratories, USA) involved application of statistics to improve the quality of voice in telephone transmission (Shewhart & Deming, 1967). The legacy Shewhart left behind on statistical thinking (on systems and processes) was taken on board and popularised among practitioners by W. Edwards Deming (1900-1993), Roland Snee (1942-), Roger Hoerl (1957-) and others (Hoerl & Snee, 2012). For example, Snee (1990) formalised the ideas of Shewhart and Deming to formulate an early definition of statistical thinking in quality improvement:

I define statistical thinking as thought processes, which recognize that variation is all around us and present in everything we do, all work is a series of interconnected processes, and identifying, characterizing, quantifying, controlling, and reducing variation provide opportunities for improvement.

Snee (1990, p. 118)

Coming back to Shewhart, he observed that in general, two types of variations exist in systems and processes: variability associated with "chance causes" and variability associated with "assignable causes"; these terms were subsequently renamed by Deming as common cause variation and special cause variation respectively (Deming, 2000; Tawn, Squire, Mohammed, & Adam, 2005; Wheeler & Chambers, 2010). Special causes are not a part of the system, but arise as result of an occurrence a special cause which is assignable to one of the so-called root factors: people (employing an untrained employee), machinery (e.g. a machine failure), material (e.g. defective batch of raw material), methods (e.g. an employee not following the prescribed work method), and

the environment; common causes on the other hand are random causes that are inherent in the system itself (Deming, 2000; Tawn et al., 2005). It is well documented in the literature that the interventions required to reduce variability due to common causes are very different from the interventions required to reduce variability due to special causes (Deming, 2000; Snee, 1990; Summers, 2010). For this reason statistical thinking emphasises the importance of understanding the distinction between a stable (predictable) process and an unstable (unpredictable) process (Deming, 2000; Tawn et al., 2005). An unstable process is a process that is subjected to special cause variation over and above the variation that is inherent in system (i.e. common cause variation).⁵

Shewhart developed a family of graphical tools, now famously known as Shewhart's control charts to examine whether or not a process is stable (Deming, 2000; Wheeler & Chambers, 2010). A control chart is a running record of periodically collected data over time showing the limits (known as control limits) within which data from a stable process is expected to lie. A control chart indicates to an operator when to take corrective action (indication of an unstable process, implying an assignable cause) and when not to do so (when there is no indication of an unstable process) (Deming, 2000; Wheeler & Chambers, 2010).

2.3.2. Statistical Thinking in Organisations

Snee (1990) observed that statistical thinking gained traction among quality fraternity due to Deming's assertion on quality: "reduce variation and you improve quality" (Snee, 1990, p. 118). Consequently reducing variation remains fundamental in statistical thinking (Britz, Emerling, Hare, Hoerl, Janis, & Shade, 2000; Snee, 1990). Experts in quality and industrial statistics show that statistical thinking can be applied at three layers in an organisation: operational, managerial and strategic (Britz et al., 2000; Hoerl & Snee, 2012). While there is an overlap, the separation between statistical thinking and statistical methods/tools/techniques (e.g. Shewhart's control charts, cause-effect

⁵ A stable process (i.e. a process that is subjected common cause variation only) is said to be predictable because when the process is stable, it is possible to quantify the variability (e.g. the variability can be expressed as a standard deviation) and thereby predict (with a certain degree of certainty) in which range an observation collected from a process (e.g. a quality characteristic of a product) is expected to be at a given point in time. For example, under the assumption of normally distributed data, an observation will lie within ± 3 standard deviations from the mean 99.73% of the time (Wheeler & Chambers, 2010).

diagram) is reasonably clearly explained in the literature (e.g. Hoerl & Snee, 2012). Statistical thinking primarily refers to contextualising, transnumeration (translating a real system into a statistical system), consideration of variation, and data collection (Pfannkuch & Wild, 2004). Statistical methods on the other hand facilitate analysing the data to make actionable conclusions (Britz et al., 2000). Figure 2.3 shows the overlap between statistical thinking and statistical methods.

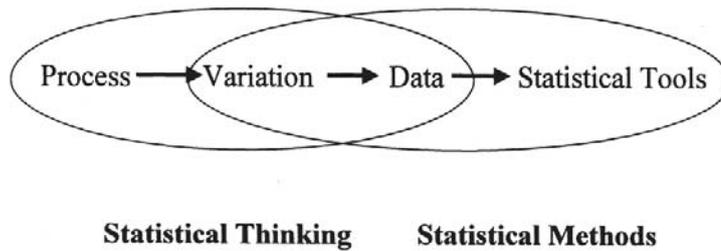


Figure 2.3: Relationship between statistical thinking and statistical method (Source: Snee, 1999)

Taking Snee’s initial ideas into consideration (Snee, 1990), the American Society of Quality (ASQ) provided an official definition of statistical thinking in 1996 to cover all three layers (operational, business, and strategic) of an organisation:

Statistical Thinking is a philosophy of learning and action based on the following fundamental principles: all work occurs in a system of interconnected processes, variation exists in all processes, and understanding and reducing variation are keys to success.

(ASQ, 1996)

The remaining subsections of section 2.3 cover the subdomains pertinent to statistical thinking.

2.3.3. Continuous Improvement

Since the advent of the *total quality* movement (in the West) in the late 1980s⁶, many different types of organisations/industries around the world began to adopt CI approaches as a new management paradigm to improve their business outcomes such as reducing waste/scrap and improving productivity (Bessant, Caffyn, & Gallagher, 2001; Caffyn, 1999; Singh & Singh, 2012). CI is the English translation of the Japanese philosophy *kaizen* (Kai, meaning do/change and Zen, meaning well or for good) (Malik, Li-bin, Ye-zhuang, & Xiao-lin, 2007; Singh & Singh, 2015). Several definitions for CI have been provided by the academia as well as by the practitioners. Bessant et al. (1994) viewed as a “company-wide process of focused and continuous incremental innovation”. The CI concept underlying the Deming management method was exemplified by Anderson, Rungtusanatham, and Schroder (1994) as “the propensity of the organisation to pursue incremental and innovative improvements of its processes, product, and services”. Bhuiyan, and Baghel (2005) defined CI “as a culture of sustained improvement targeting the reduction of waste in all systems and processes of an organisation”.

CI is regarded in the literature as a company-wide process that focuses on continuous incremental innovation to reduce waste and improve product quality with the involvement from top management to the workers on the shop floor; the nature of continuous incremental innovation includes small step, high frequency, short cycles of changes, which in aggregate form provides significant impact on manufacturing performance (Bessant et al., 2001; Bhuiyan & Baghel, 2005; Dale et al., 2013; Terziovski & Sohal, 2000). Proponents of CI promote it as a universal paradigm, that as a quality improvement proposition that holds true across all manufacturing, service, as well as public and non-profit organisations (Bessant et al., 2001; Bhuiyan & Baghel, 2005; Douglas, Jenkins, & Kennedy, 2012; Singh & Singh, 2015).

Singh and Singh (2015) observe that CI can be used to achieve five outcomes: minimise changeover/setup time, defects reduction (zero defects being the aim), waste reduction

⁶ Total quality (meaning a leadership driven culture where everybody in the organisation is involved in problem solving related to quality) is regarded as a concept that the West borrowed from Japan, in an attempt to catchup with Japan, who enjoyed phenomenal success in capturing the product market with superior quality products since the world war II (Dale, Van Der Wiele, & Van Iwaarden, 2013).

(zero waste being the aim), minimising delays (zero delays being the target), and minimising breakdowns (zero breakdowns being the aim). It appears Lean (see section 2.2.3) is also a causal antecedent of all of the above five outcomes; this also evident from the fact that all 10 tools and techniques identified by Singh and Singh (see Singh & Singh, 2015, p. 81-82) to achieve the five CI outcomes are Lean tools and techniques (in developing the conceptual model in section 4.3 of the fourth chapter the author argues that Lean drives CI, which in turn enables the Lean outcomes). The author observes that *statistical process control* (SPC) is conspicuously absent in Singh and Singh's 10 CI tools. SPC is about continuous monitoring and controlling the process statistically (e.g. using Shewhart's control charts, process capability analysis) and CI begins with process control. In Deming's own words: "problems of improvement commence once you achieve statistical control" (Deming, 1982). However, Singh and Singh contend that CI /kaizen is an important element in total quality; as an example they cite Deming's 5th point (Deming prescribed 14 points on quality and productivity improvement): "Improve constantly and forever the system of production and service, to improve quality and productivity" (see Deming, 1982 for details). Arguably Singh and Singh fail to realise that SPC is the tool of choice to monitor a process to determine whether or not improvement is needed.

Bhuiyan and Baghel (2005) advocated that firms establishing CI may find it helpful to view CI implementation as a long term process which follows an iterative cycle. The most well subscribed iterative cycle in the literature is Shewhart's/Deming's Plan, Do, Check (or Study), Act (PDCA) cycle of CI; in this cycle "plan" refers to defining the problem, understanding it and developing solutions; "do" refers to implementing the chosen solution; "check" refers to studying the system to determine how well the intervention has worked; "act" refers to standardising the solution if it has worked and if not to find out why and revert back to the "plan" stage to develop a new/improved solution (Dale et al., 2013; Singh & Singh, 2015). In PDCA or other similar CI cycles⁷ the emphasis is on tracing back to the root causes that cause the problem (e.g. excessive waste of raw material) and continue working (i.e. cycle) until the problem is resolved (Bañuelas & Antony, 2003; Caffyn, 1999).

⁷ For example, the DMAIC cycle in the Six Sigma approach (section 2.3.5) and DMADV cycle in the DFSS approach (section 3.5.1).

In its mentioned in the literature (e.g. Bhuiyan & Baghel, 2005; Filho & Uzsoy, 2011; Radnor, Walley, Stephens, & Bucci, 2006) that CI should typically be used in conjunction with another quality or process improvement approach such as Lean Six Sigma, and total quality. The argument is that historically, the hybrid approaches have found to overcome the weakness of using one approach alone (Bhuiyan & Baghel, 2005). While the researcher agrees that hybrid improvement approaches (e.g. Lean with Six Sigma, robust design with Six Sigma) have found to be effective (covered elsewhere), in her view, it is not prudent to compartmentalise CI as a specific quality/process improvement approach because CI is subsumed in many improvement approaches, for example in Lean, Six Sigma and total quality.

Imai (1986) and Bessant (1992) observed that even though Japan received significant improvements in productivity, quality, flexibility and responsiveness to outperform through CI /kaizen, western organisations continue to pursue radical solutions through big step improvement (Bessant, 1992; Imai, 1986). There have been several studies (e.g. Aoki, 2008; Saka, 2004; Yokozawa, Steenhuis, & de Bruijn, 2012) those examined the factors that contribute to successful transfer of kaizen to cultures outside Japan. For example, Yokozawa et al. found that successful adoption of kaizen requires “organic structures” and “clan-oriented cultures” and that kaizen is likely to be unsuccessful in high power distance cultures. There have also been studies (e.g. Al Smadi, 2009; Detert, Schroeder, & Mauriel, 2000) that examined the characteristics of organisational culture in which CI works. Ahmed, Ann, Loh, and Zairi (1999) assert that the organisational culture is the driver that constantly strives employees towards engaging in CI activities and organisational learning. The study by Detert, Schroeder, and Mauriel, which still remains one of the comprehensive studies in identifying the organisational cultural dimensions that support kaizen (and total quality), provides an elegant eight dimensional framework to examine the nature of a kaizen organisation across each dimension.

It is also mentioned in the literature that although CI, as applied to organisations, is essentially a team based approach, it is embedded in all aspects of one’s working life (Caffyn, 1999; Imai, 1986; Singh & Singh, 2015). Finally, Womack and Jones (2003) and others (e.g. Arnheiter & Maleyeff, 2005; Imai, 1997; Yamamoto, 2010) assert that application of a combination of kaizen and kaikaku events/interventions (big-step

improvement or radical improvement) lead to endless improvement, as long as they are correctly used.

2.3.4. Big-Step Improvement

Every organisation needs to improve its processes continually to remain competitive in a continuously changing environment (e.g. technological changes, changes in the competitive environment, changes in the economic environment, changes in the demographics and so on). It is mentioned in the literature that in some environments such as in environments in which product designs or processes need to be changed rapidly to cater to new demands, kaizen alone is not effective; an organisation needs to make radical improvements (these are discontinuous improvements) in their products (or services) and processes (Arnheiter & Maleyeff, 2005; Singh & Singh, 2015; Yamamoto, 2010). The reader should note that keeping with the lexicon of Deming (e.g. Deming, 2000), the American Society for Quality (e.g. ASQ, 2013), and the international quality management system standards (e.g. Standards Australia/Standards New Zealand, 2008), the author uses the term continual improvement to mean both CI (kaizen) and discontinuous improvement (i.e. big-step improvement, which is also known in other names such as kaikaku, radical improvement, and innovation).

Ranganathan (2012) maintains that kaikaku or radical improvement takes place when there is not enough improvement to be gained from Kaizen activities. Ranganathan as well as Yamamoto maintain that kaikaku activities need high capital investment and a technology oriented effort as opposed to a people oriented effort in kaizen (Ranganathan, 2012; Yamamoto, 2010). Imai (1986) discussed on different perspectives of CI (kaizen) activities and contrasted these with those in big step or radical improvement (kaikaku) activities. The summary of the two approaches as summarised by Imai, is shown in Table 2.1 below.

Imai (1986) show that kaizen is required to sustain a kaikaku event because once the new system has been installed through new technology or an innovation, in the absence of kaizen, the system gets subjected to steady deterioration . Therefore (as also has been mentioned earlier) kaizen and kaikaku are complementary (Imai, 1986; Yamamoto, 2010).

Table 2.1: Kaizen Vs Innovation (Kaikaku) (Adopted from Imai, 1986)

	Kaizen	Innovation (Kaikaku)
Effect	Long-term and long lasting but undramatic	Short-term but dramatic
Pace	Small steps	Big steps
Timeframe	Continuous and incremental	Intermittent and non-incremental
Change	Gradual and constant	Abrupt and volatile
Involvement	Everybody	Select few “champions”
Approach	Collectivism, group efforts, systems approach	Rugged individualism, individual ideas and efforts
Mode	Maintenance and improvement	Scrap and rebuild
Spark	Conventional know-how and state of the art	Technological breakthroughs, new invention, new theories
Practical requirements	Requires little investment but great effort to maintain it	Requires large investment but little effort to maintain it
Effort orientation	People	Technology
Evaluation criteria	Process and efforts for better results	Results for profits
Advantage	Works well in slow growth economies	Better suited for fast growth economies

2.3.5. Six Sigma

In the literature Six Sigma is viewed in different ways: as a mature quality system⁸ of an organisation (e.g. Hilton, Balla, & Sohal, 2008; Schroeder, Linderman, Liedtke, & Choo, 2008; Summers, 2009), a methodology (e.g. Antony, 2004; Snee, 2004), and a quality performance metric (e.g. Dasgupta, 2003), and all or a combination of the above (e.g. Antony, 2004; Evans & Lindsay, 2015). Whichever way one views Six Sigma, understanding and reducing variation remains a key objective in Six Sigma (Schroeder et al., 2008; Snee, 2004). As such Six Sigma becomes a very important subdomain of statistical thinking (Britz et al., 2000; He & Goh, 2015; Hoerl & Snee, 2012).

The Six Sigma quality system was initially developed in Motorola to achieve competitive advantage by reaching phenomenally high levels of product compliance: a high process capability that translates to as low a defects rate as 3.4 defects per million opportunities (DPMO) (Britz et al., 2000; Hoerl & Snee, 2012). Later, Six Sigma was

⁸ A quality system is the organisational subsystem that contains the ingredients (e.g. the philosophy, people, knowledge, methods, tools etc.) to design, develop and deliver what the customer wants; a more narrower view (typically implied in quality management systems standards) of a quality system is the documentation that are required to assure quality to the customer (Evans & Lindsay, 2015).

introduced in General Electric (GE), Allied Signal and other organisations with remarkable success (Britz et al., 2000; Hoerl & Snee, 2012). The reader should note that the defects rate 3.4 DPMO is what Six Sigma is, when Six Sigma is used as a quality performance (or process capability) metric (Hoerl & Snee, 2012). Figure 2.4 shows what a Six Sigma process means as a quality performance (or process capability) metric.

A Six Sigma process (as a process capability metric) is defined as a process whose centre is as far a distance as 6σ from the nearest specification limit (σ being the standard deviation of the process) in the short run and a 4.5σ distance in the long run (Montgomery, Runger, & Hubele, 2011). Implicit in this definition is the notion that the mean value (centre) of the process does drift a distance of 1.5σ from the desired value in the long run (see Figure 2.4). It is easy to show statistically (assuming a normal distribution) that under this long run scenario, only 3.4 observations in a million fall outside the specification limits (see Montgomery et al., 2011, p. 464). The researcher observes that Six Sigma is usually associated with SPC (Montgomery et al., 2011 is typical), in the sense, a Six Sigma project typically begins and ends with SPC (or in general terms, quality by control).⁹

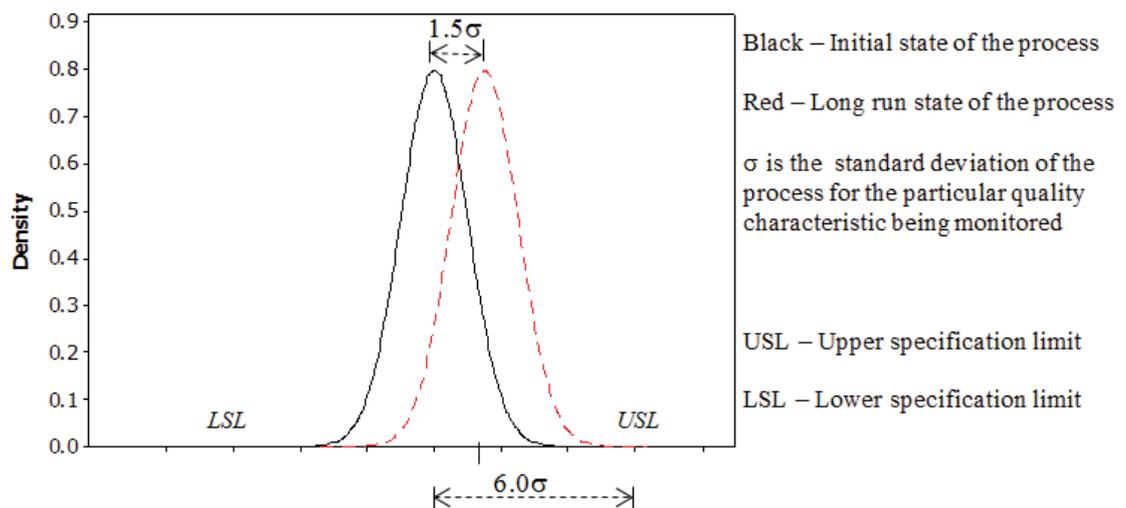


Figure 2.4: Explaining Six Sigma as a quality performance metric (adopted from Montgomery et al., 2011, p. 464)

⁹ Design for Six Sigma (DFSS), which is a variant of Six Sigma in different, in the sense DFSS begins at the product design and development stage (details in section 3.5.1).

Schroeder et al., (2008) viewed Six Sigma as a leadership driven organisational “meso-structure” (meaning a structure that runs parallel to the organisation’s hierarchical structure) that uses a “structured problem solving method” in strategically selected quality improvement projects. According to them the individuals in the meso-structure (in the hierarchical order from top to bottom) are the leaders (called champions) who sanction projects and allocate resources, project leaders (called black belts) and less senior members (often called green belts) in the cross-functional quality improvement team. The structured problem solving method of Define (D) → Measure (M) → Analyse (A) → Improve (I) → Control (C) (hence the acronym DMAIC) is well documented in the Six Sigma literature (Evans & Lindsay, 2015; Schroeder et al., 2008).

Breyfogle (2003) observes that while reducing variation, reducing defects, increasing productivity, and enhancing customer satisfaction are the main goals being pursued in Six Sigma, these goals nevertheless tie-up with “profitability” (typically measured using the return on investment metric); Breyfogle asserts that in Six Sigma, the estimated profitability becomes the deciding criterion in selecting projects. It has also been argued that the goals of Six Sigma are also closely related to customer value and as such, Six Sigma projects could benefit from the application of Lean principles. The next section (section 2.3.6) covers this topic.

2.3.6. Lean Six Sigma

Conceptually, Lean Six Sigma (LSS) is viewed in the literature as a process improvement approach that leverages on the combined application of Lean and Six Sigma approaches to derive the synergies of applying both approaches together, rather than in isolation (Arnheiter & Maleyeff, 2005; Pepper & Spedding, 2010; Snee, 2010). Using the salient features of Lean (pull production) and Six Sigma (process improvement through structured problem solving), Snee (2010) shows how Lean production systems (pull systems) and process improvement projects (Six Sigma projects) could co-exist to enhance customer value, by eliminating waste and non-value adding activities. Snee also asserts that LSS projects also require CI to sustain the improved performance achieved because process performance tends to decline over time. Within a systems thinking context, Snee’s assertion that processes deteriorate over

time can be viewed as “entropy” (for a detailed discussion on properties of a system see Kast & Rosenzweig, 1972).

Zhang, et al. (2012) reviewed 116 scholarly articles (case studies) on LSS to identify how Lean approaches complement Six Sigma approaches (and vice versa) in practice. They found that in general, one approach appears to be offsetting the limitations of the other, which enables an organisation to achieve more holistic improvements to its processes and outcomes. Similar sentiments (via conceptual papers) have been expressed by Bendel (2006), Snee (2010) and others. For example, Bendel shows that while Lean approaches rely on technically simple problem solving tools and techniques that are mainly geared to reduce waste and Six Sigma approaches rely on technically sophisticated tools and techniques that are mainly geared to reduce variation, there are instances where both approaches are necessary to improve a process effectively. What Bendel seems to imply is that variation reduction and waste reduction need not be mutually exclusive (the researcher accepts this position). However, Bendel contends that any effort towards building a universal theory on LSS (by linking Lean concepts and Six Sigma concepts together) becomes questionable.

Using a single organisation as a case study, Thomas, Barton, and Chuke-Okafor (2008) designed, developed and implemented a LSS model (this model combines Lean concepts and Six Sigma concepts) that predicts and explains process outcomes in a small to medium sized manufacturing enterprise, in terms of product quality, cost, efficiency, and delivery. Their model posits “DoE-based experimentation” as the medium that links Lean concepts with Six Sigma concepts to solve “critical to quality” problems. The model also explains how a culture of CI is created through LSS. It is interesting to note that there isn’t a single published study that examines the adaptation of LSS in an apparel manufacturing environment. However, there are several LSS implementation case studies (e.g. Timans, Antony, Ahaus, & Van Solingen, 2012; Vinodh, Gautham, & A., 2011; Vinodh, Kumar, & Vimal, 2014) on other manufacturing sectors.

Hoerl and Snee (2010) show that there is nothing new in LSS. They claim that LSS is a technique that capitalises on judicious selection of existing principles, tools and techniques. According to Hoerl and Snee this is one reason why academia have been

slow to embrace LSS compared to innovative quality improvement methods such as Taguchi methods (covered in the next chapter).

2.4. CHAPTER CONCLUSION

This chapter was dedicated to reviewing the literature on Lean Manufacturing Systems (the context within which RPD is applied) and two inter related concepts statistical thinking and CI. Through the review of the literature on Lean Manufacturing Systems (section 2.2), the researcher found that although the primary aim of Lean is CI of operational performance to add value to the customer and the organisation, it is possible to build additional value (see Figure 2.2) through Lean at the design stage of the product, through superior product quality (e.g. Hines et al., 2004). This will be one of the primary elements that will be carried forward to the next chapter in framing the research questions. Another primary element of Lean that will be carried forward to the next chapter is the emphasis on problem solving (section 2.2.3), which is also common in Taguchi's RPD approach.

The researcher also reviewed the subject areas Six Sigma (section 2.3.5) and LSS (section 2.3.6) for two reasons. Firstly, reducing variation remains a central objective in these approaches, which is also common in Taguchi's RPD (see next chapter) although the latter is a product design concept. The researcher showed that Six Sigma and LSS typically originate from quality by control activities (e.g. SPC) and hence the notion that quality needs to be built into the project at the design stage is not subsumed these methods. Secondly, the fieldwork the researcher conducted (Chapter 5) to reduce variation at the Lean apparel plant was a LSS project in every respect but the name.

The literature related to the study is continued to next chapter (Chapter 3), which primarily reviews the literature on robust parameter design approaches. The next chapter also shows the research questions based on the knowledge gaps identified through the literature review.

CHAPTER 3

QUALITY AND ROBUST PARAMETER DESIGN

"Do not use an axe for a thing that you can do with your fingernail".

—A Sinhalese Proverb

3.1. INTRODUCTION

This chapter continues the literature review that initiated from the previous chapter. Since the overall aim of this study is to understand the applicability of Taguchi's RPD approach in a mature Lean apparel manufacturing environment, a considerable portion of this chapter was dedicated to the review of literature on RPD approaches. The knowledge gaps identified from the literature review presented in the previous chapter and this chapter and as well as the research questions are presented in this chapter. The subsections of this chapter are organised as follows.

Section 3.2 introduces, in the order of maturity, the three primary ways in which quality control and quality assurance is accomplished in a manufacturing organisation: quality by inspection (QbI), quality by control (QbC), and quality by design (QbD). RPD is an important subdomain of QbD. Section 3.3 provides a synopsis of the traditional/classical DoE approach, as a precursor to the literature on RPD, which is presented in the next section (section 3.4). Section 3.4 on RPD covers the literature on the theoretical foundations of Taguchi's approach to RPD (section 3.4.1), the key debates on this approach (section 3.4.2), and the alternative RPD methods relevant to the study (section 3.4.3). Section 3.5.1 provides a synopsis of Design for Six Sigma (DFSS) for the purpose of comparing DFSS with integration of Taguchi's RPD approach within a Lean context. Section 3.5.2 provides a rundown of alternative robust design approaches for the purpose of comparing these with Taguchi's RPD approach. Section 3.6 begins by highlighting the knowledge gaps (section 3.6.1) that emerge from the literature to pose the four *research questions* (section 3.6.2) of the study. Finally, section 3.7 concludes the chapter by providing a summary of what was learnt from the literature.

3.2. PRODUCT QUALITY ASSURANCE

Traditionally quality is controlled *either by inspection* (inspecting the incoming goods or finished goods to weed out the nonconforming ones) or by *control*: continually monitoring the process and taking corrective action when necessary (Dale et al., 2013; Rahman, 1995; Summers, 2010). These approaches provide little incentive for a manufacturer to embed quality into the design stage of the product. On the other hand, QbD aims to build quality at the design stage of the product (Antony, 2014; Rahman, 1995; Roy, 2010; Samson & Sohal, 1990).

3.2.1. Quality by Inspection

Quality by inspection is the oldest known ‘scientific’ method used to control the quality of incoming goods into a production process, or the finished goods produced by the process. Inspection, which can range from 100% inspection to a sample-based inspection (which can be based on a simple sampling plan or a very elaborate sampling plan), has two main disadvantages. Firstly, the inspection approach fails to acknowledge the fact that all processes show variation (which can come from causes inherent to the system or causes external to the system) and that understanding the root causes of variation is the key to reduce nonconformities. Secondly, inspection does not involve problem solving as such (e.g. root cause analysis) and consequently, inspection fails to use the knowledge of the operations staff either in quality control or quality improvement (Dale et al., 2013; Deming, 2000; Rahman, 1995).

W. Edwards Deming, one of the principal quality gurus of the 20th century, was one of the earliest to discuss the fallacies of inspection, both at organisational level and societal level. Deming once mentioned that “the right quality and uniformity are foundations of commerce, prosperity and peace” of a society (cited in Howard, 1992). He argued that cost to a company for losing customers due to poor quality is infinite (Gunter, 1987). To him, poor quality is caused due to the deviation of functional characteristics of the product from their specified values (or attributes), due to variation. Deming asserted that “quality by inspection” is an obstacle towards efficiency and effectiveness. He argued that quality by inspection is late, ineffective and that quality cannot be improved by inspection (Deming, 1982; Walton, 1989). Quality by control or (more specifically)

quality by statistical process control of the processes at different stages of production was the alternative proposed by Deming.

3.2.2. Quality by Control

Quality by control acknowledges the fact that variation is inherent in any process and that this variation can be due to either causes inherent in the process (“common causes”) or causes external to the process (“special causes”). Deming showed (e.g. Deming, 2000) that the action required to reduce the two types of variations are totally different from one another and that wrong actions add cost to the company as well as to the end user. Deming asserted that understanding the type of variation without ambiguity and controlling the process (statistically) continuously (to bring the process under statistical control) are the key to process improvement (Deming, 2000; Montgomery & Runger, 2010).

Two unique tools are invariably associated with quality by control: Shewhart’s control charts and the Plan (P)-Do (D)-Check (C)-Act (A) continuous cycle of quality improvement (Deming, 2000; Rahman, 1995; Summers, 2010). A Shewhart control chart is a chart that shows time-ordered data (which can be physical measurements from the product or process or specific attributes of the process such as defects rates) graphically; it is essentially a statistical tool that is used to verify whether or not a process is stable at any given point in time (Dale et al., 2013; Deming, 2000; Summers, 2010). A stable process is defined as a process that is subjected to common cause variation only. Deming asserted that understanding whether or not the system/process is stable is absolutely essential before deciding whether it is necessary to improve the process, so as to reduce variation. The PDCA problem solving cycle on the other hand is a sequential, on-going approach of problem solving (e.g. variation reduction) that involves organisation-wide involvement (Dale et al., 2013; Summers, 2010).

Another important concept articulated by Deming, in connection with quality by control, is “supplier development” (Anderson et al., 1994; Dale et al., 2013). Deming proposed that management has to collaborate with the suppliers to improve the quality of the raw material and/or components that are sourced from the suppliers. Deming argued that switching from one supplier source to another on random variation does not reduce but increase the occurrence of special cause variation.

In quality by control, once the process designers are able to eliminate the occurrence of special cause variation, action can be taken to reduce common cause variation; that is, reducing the inherent variation of the process. This can be accomplished by redesigning the manufacturing process through a major change or by making the process (or the product that the process manufactures) robust or insensitive to factors that cause the common cause variation (noise), by setting the process input parameters (control factors) at specific predetermined levels (Allen, 2010; Joseph, 2007). Redesigning the process is a costly option as it requires capital (e.g. new machinery, equipment, staff training). Unfortunately, quality by control defaults to the premise that reducing common cause variation (inherent process variation) requires a major process redesign, which in turn requires top management support (Does & Roes, 1996; Rahman, 1995; Young & Karr, 2011). Therefore, it can be argued that while quality by control provides a scientific approach towards reducing variation whilst in production, because reducing inherent variation of a process is deemed costly in this approach (Deming's propositions are partly attributable for this), quality by control does not provide a major incentive to minimise variation in a stable system; instead it encourages limiting variation to specified limits (tolerances).

3.2.3. Quality by Design

Quality by design refers to building quality into the product (and the processes that produce the product), meaning providing a superior product to the customer in the first place (Dale et al., 2013). Building products that stand robustly against the variability of uncontrollable variables that exist out there (e.g. in a factory, outside the factory when the product is put into use by the customer) in an *efficient manner* is one important product design and development aspect. This brings to the concept of quality by robust parameter design (RPD), which is now a well-accepted *quality by design* approach (Montgomery, 2013; Roy, 2010; Taguchi & Clausing, 1990).

Setting the process input parameters to achieve robustness is an off-line approach (i.e. a procedure undertaken at the product development stage rather than at the manufacturing stage) based on carefully designed industrial experiments. While conducting industrial experiments to set the optimal operating parameters of a manufacturing process is by no means inexpensive, compared to alternative approaches of achieving robustness, it is an

economic option as it does not usually require financial capital investment in the form of new machinery and equipment. In the literature, making a product or process robust against the noise (variability of uncontrollable factors), is known as the *robust engineering* (RE) or the *robust design* (RD) (Allen, 2010; Montgomery, 2013; Roy, 2010). RPD, a term often used interchangeably with RD, relies on adjusting the process parameters rather than investing in excessive capital such as designing and acquiring new machinery and equipment (in part, this equates to tightening the tolerances of the machinery, equipment, and other major components of production) to achieve robustness—that is invariance of product’s functional characteristics (Montgomery, 2013; Ross, 1996; Roy, 2010).

3.3. THE TRADITIONAL DOE APPROACH

Box, Hunter, and Hunter (2005) assert that statistically designed experiments, which are also known as design of experiments are part and parcel of discovery and problem solving in engineering and other science disciplines (Box, 1993; Montgomery, 2013). In the DoE literature, three different types of experimental designs are mentioned: factorial designs (which can be divided into full factorial and fractional factorial designs), response surface designs, and evolutionary operation (Box et al., 2005; Steinberg, 2014). Montgomery (2013) depicts an experiment-based problem solving cycle (Figure 3.1) in seven essential steps.¹⁰ A brief description of each step follows.

¹⁰ It appears that Montgomery’s model shown in Figure 3.1 does not cover the evolutionary operation (EVOP) procedure. EVOP concerns adjusting a live process to evolve into a better operating condition by adjusting few (typically two) factors in a cyclical position. As such, some steps in Figure 3.1 do not apply to EVOP, for example, the question of proposing and refining the model (Box 3 in Figure 3.1) does not arise.

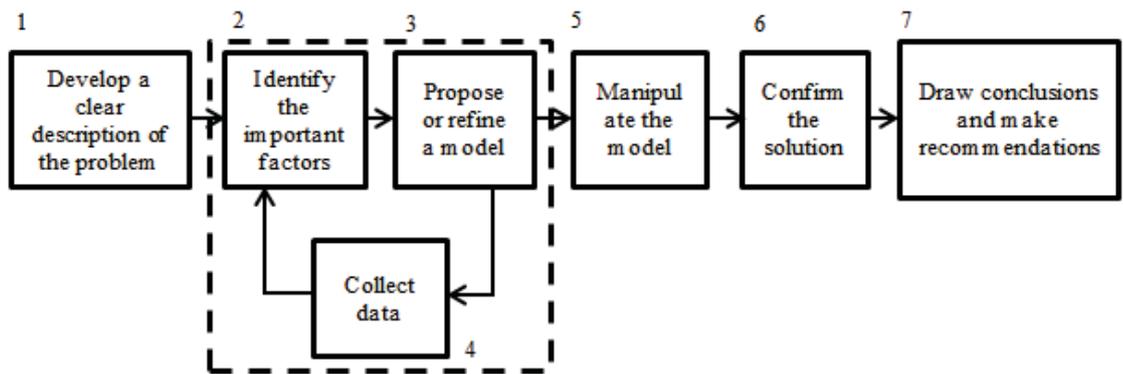


Figure 3.1: The engineering problem solving method (source: Montgomery, 2013)

Like in any problem solving matter, defining the problem and succinctly describing it (Step 1), is strongly emphasised in the literature (Box et al., 2005; Montgomery, 2013). At the early stage of learning about a process, the problem to be solved could be, for example, identifying the important factors that need to be manipulated (out of many possible factors) in future experiments (to achieve the end goal), without wasting too much resources; a *fractional factorial experiment*, where a large number of factors (variables) are simultaneously manipulated at few selected combinations of factor settings (out of all the possible combinations of factor settings, given the number of levels at each factor is to be manipulated) becomes the experiment of choice in such a situation (Box et al., 2005).¹¹ At the final stages of learning, where a “*response surface*” DoE methodology such as the central composite design becomes the natural choice (Box et al., 2005), the problem definition (still in Box 1, Figure 3.1) could be for example, mapping the relationship between the most influential factors (previously identified) and the process output or outcome (e.g. the yield) in the region in which the desired outcome exists (Montgomery, 2013). Three types of the desired outcomes are mentioned in the literature: maximising the response (which is usually the case if the process yield is the response variable), or achieving a target response (which is the case when producing a product that needs to conform to a certain specification), or

¹¹ For example, the engineers may guess that there are as many as seven potential factors that affect their process outcome (for example, in a chemical production process, the yield). If they decide that each factor should be manipulated at two levels (which is typical) there are $2^7 (= 128)$ ways in which the seven factors could be manipulated. Just for the purpose of identifying the influential (important) factors, the engineers would not waste resources by way of running 128 experimental runs; instead, they would decide to run, say 1/16th fraction of the full complement of runs, which boils down to just running 8 experimental runs (Montgomery, 2013).

minimising the response (which is the case if the response is not desired, such as the impurity level in a composite material that is produced).

At the very first stage of learning, the experimenters need to identify the potentially important factors (Box 2) from whatever process knowledge they possess (Montgomery, 2013); in the field of quality management, tools such as brainstorming and Pareto Charts are prescribed in the literature to facilitate this process (Dale et al., 2013; Summers, 2010). At the initial stage/s of learning an experimenter would propose a linear model (also no interaction between factors) relating the response with the factors that they identified (Box 2). Thereafter they would collect the data (Box 3) and fit the model to data, in order to refine the model (back to Box 2). The *statistical literacy* required to perform these tasks include knowledge on the principles of data collection, the awareness of the existence of confounding factors that can affect the results and precautions that need to be taken to minimise their effects (e.g. “blocking”), and analytical skills such as *the analysis of variance* (ANOVA) and *multiple regression* (Box et al., 2005; Montgomery, 2013).

Confirming the solution (Box 6 in Figure 3.1), meaning confirming the statistically determined optimal solution with a *new set of data*, becomes paramount in the final stages of learning because this solution has commercial consequences (Montgomery, 2013; Roy, 2010). The conformation step (Box 6) also epitomises the most fundamental principle in statistical thinking: variation is inevitable in any phenomenon (Hoerl & Snee, 2012).

“Sequential learning” is a principle that is heavily emphasised in conventional DoE literature (Montgomery, 2013; Tanco, Viles, Ilzarbe, & Alvarez, 2009). Sequential learning refers to building knowledge in a sequential fashion by conducting one small experiment (meaning a low commitment of resources) at each cycle of learning, by answering only one of few questions in each cycle (Montgomery, 2013; Tanco et al., 2009). This is also a reason why a clear and concise description of the problem to be resolved (Box 1 in Figure 3.1) is important in each learning cycle. The principle of learning sequentially, (i.e. iteratively) using a small experiment at each time is known as the “*keep it simple and sequential*” (KISS) principle in the conventional DoE literature (Montgomery, 2013). This principle is based on the proposition that an experimenter would know very little about the process being investigated at the beginning, and

therefore they should not take the risk committing vast amounts of resources upfront to achieve the final objective (Montgomery, 2013; Tanco et al., 2009). Thus the KISS principle is viewed as a risk minimisation strategy (Box et al., 2005).

Another important principle that is highlighted in the DoE literature is varying all the experimental factors simultaneously, instead of varying one-factor-at-a-time (OFAT), keeping other factors fixed (Czitrom, 1999; Montgomery & Runger, 2010; Tanco, Viles, Ilzarbe, & Álvarez, 2007). It is mentioned in the literature that OFAT experiments are inefficient and unreliable because of possible interactions between factors (Czitrom, 1999; George, Raghunath, Manocha, & Warriar, 2004; Gunter, 1987; Montgomery & Runger, 2010). Characterising the process by establishing a functional relationship (i.e. a mathematical relation of the form $y = f(x)$) between the response (y) and the factors (the independent variables x) empirically through data collection and model fitting is a salient feature in conventional DoE (Box et al., 2005; Khuri & Mukhopadhyay, 2010; Montgomery, 2013).

Implicit in the traditional approaches is the notion that it is the statistician (or the statistically literate engineer) who plans the experiments and analyses the results (Mayer & Benjamin, 1992; Roy, 2010; Tay & Butler, 1999). The traditional approach does not require a great deal of prior process knowledge; knowledge emerges through statistical analysis such as ANOVA, regression analysis, model adequacy diagnostics, factorial plots and so on (Gunter, 1987; Montgomery, 2013; Roy, 2010).

It is commonly acknowledged in the literature (e.g. Box, 1993; Montgomery, 2013) that until Genichi Taguchi introduced the RD concept (Taguchi, 1986) and the need to design experiments to reduce the variation of the response, DoE experiments were designed towards achieving a certain response value (on average) only; designing experiments to model response functions to capture variation (dispersion) became common in conventional DoE with the advent of the Taguchi's RPD concept; concurrently, applications of DoE methods advocated by Taguchi (commonly known as Taguchi methods) also increased (Montgomery, 2013) with one stream getting cross-fertilised from the other to add the richness to each stream. For example, some procedures that are now being considered as standard in Taguchi methods actually come from the recommendations made by statisticians such as Box (e.g. Box, 1988) on working around some of the possible pitfalls of Taguchi's data analytic framework

(section 3.4.2.3). Today, the academia and the practitioners in the field of quality are blessed with a rich body of knowledge on designing experiments to reduce variation. Six Sigma (see section 2.3.5) is one of the well-established quality systems that use DoE to reduce variation (Allen, 2010; Evans & Lindsay, 2015).

3.4. THE ROBUST DESIGN APPROACH

Robust Design (RD) can be defined as an engineering approach that aims to minimise sensitivity of products and processes to variations that transmit from external and internal environmental factors (e.g. the user conditions, temperature, variability of material), commonly known as noise in statistics (Box & Bisgaard, 1987; Box et al., 1988; Roy, 2010). Typically, a RD is accomplished through statistically designed experiment/s (more commonly known as DoE) to identify optimum design parameter settings (i.e. the RPD approach) to operate a process is a revolutionary approach in quality engineering. As Genichi Taguchi (1924-2012), the inventor of the RPD approach asserted “the robustness of products are more a function of good design than of on-line quality control” (Taguchi & Clausing, 1990).

In the literature, designing products (or processes) that are robust against sources that create variability is not considered as something that was invented by Genichi Taguchi (Box et al., 1988; Montgomery, 2013). Montgomery explains this succinctly:

Product and process designers/developers have been concerned about robustness issues for decades, and efforts to solve the problem long predate Taguchi’s contributions. One of the classical approaches used to achieve robustness is to redesign the product using stronger components, or components with tighter tolerances, or to use different materials. However, this may lead to problems with overdesign, resulting in a product that is more expensive, more difficult to manufacture, or suffers a weight and subsequent performance penalty.

(Montgomery, 2013, p. 555)

The solution Genichi Taguchi came up with to overdesigns and related problems (e.g. cost) as an engineer was a DoE method known as the *robust parameter design* approach (Box et al., 1988; Montgomery, 2013). However, because the terms “robust design”

(RD) and “robust parameter design” (RPD) are often used interchangeably in the literature (e.g. Gremyr, Siva, Raharjo, & Goh, 2014; Jones, 2014; Robinson, Borrer, & Myers, 2004; Shoemaker, Tsui, & Wu, 1991) this thesis also uses the two terms interchangeably.

In this thesis, the researcher reviews the literature, mainly from the point of view of RD methods advocated by Genichi Taguchi as well as the alternative DoE methods advocated by the statisticians (response surface alternatives) to overcome some issues in Taguchi’s RD/DoE approaches (see section 3.4.3). However, it is important to note that RD, as understood at present, involves at least three types of RD methodologies: Taguchi’s RD approach and the response surface alternatives (these are typically known as Type I robust designs), robust optimisation approach (typically known as Type II robust designs), and the axiomatic design approach (Allen, Seepersad, Mistree, & Savannah, 2006; Park, Lee, Lee, & Hwang, 2006). The robust optimisation approach and the axiomatic design approach are emerging approaches (currently not very widely used in the industry but shows great promise) that are not considered by the researcher as methods of quality improvement in a Lean apparel manufacturing environment. Brief introductions to the robust optimisation approach and the axiomatic design approach methods follow.

Robust optimisation (RO) is a robust design approach that takes into account the uncertainty (variability) of design parameters (Bertsimas, Brown, & Caramanis, 2011; Beyer & Sendhoff, 2007). Mathematically, the RO task is presented as follows:

Optimise f_x (the objective function; x refers to design parameters)¹²

Subject to: $g_i(x) < 0, i = 1, \dots, I$ (the inequality constraints)

$h_j(x) = 0, j = 1, \dots, J$ (the equality constraints)

In RO, the optimisation is achieved through an automated procedure (as opposed to conducting a statistically designed experiment as in Type I robust designs) powered by mathematical programming and computer assisted direct search methods (Beyer &

¹² The objective function need not necessarily be expressed in mathematical format (Beyer & Sendhoff, 2007).

Sendhoff, 2007). From a practical perspective, in robust optimisation, the engineer aims to design a product/component/system whose functional performance remains stable for relatively small perturbations of the design parameters, due to whatever reason (Ben-Tal & Nemirovski, 2002).

The axiomatic design (AD), advanced by Suh (1998), is a general design framework meant to design high quality products and systems. The AD pivots on two axioms that a good design should possess. Axiom 1 pertains to a design that should satisfy multiple functional requirements (FRs), which is typical to any product/system design. This axiom holds that “an optimal design always maintains the independence of functional requirements” (Park, 2007, p. 17). Axiom 2, known as the “independence axiom”, holds that “in an acceptable design, design parameters and functional requirements are related in such a way that a specific design parameter can be adjusted to satisfy its corresponding functional requirement without affecting other functional requirements” (Park, 2007, p. 18).

Exploiting the independence axiom, the relationship between functional requirements (say, in a product) and design parameters can be expressed in matrix format as follows.

$$FR = A*DP$$

Where FR is a vector containing n number of functional requirements; A is an $n \times n$ square matrix; DP is a vector containing n number of design parameters. The engineering sequence of a product design based on the AD approach passes 4 sequential domains: *the customer domain*, *the functional domain*, *the physical domain*, and *the process domain*. In the customer domain, the engineer determines the customer needs (customer attributes) of the product (or system). In the functional domain, the engineer transforms the customer needs into functional requirements in engineering terms (e.g. Nm, kW etc.).¹³ In the physical domain, the engineer determines the design parameters to satisfy the functional requirements, which is the axiomatic robust design process for the most part. In the process domain, the engineer determines the production variables from the design parameters (Suh, 1995). According to Suh (1995), an AD is a

¹³ Generally these two domains are handled in quality function deployment (QFD), which is a well-established sub-discipline in quality (Akao & Mazur, 2003).

systematic process of designing high quality products and systems using matrix methods.

3.4.1. Taguchi's Robust Parameter Design Approach

Taguchi claimed that the quality characteristic of a product (or process) becomes variable because the environmental noise (meaning, variability that stem from the uncontrollable factors) transmit their variations to the response of the system, which is the quality characteristic being measured (Taguchi, 1986; Taguchi et al., 2000). Therefore Taguchi highlighted (as a necessary first step to reduce variability) the importance of identifying specific environmental factors that create the noise, which can come either from the internal factors (e.g. component wear, piece-to-piece variation in the components) or the external factors (e.g. external environmental factors such as temperature and humidity) (Roy, 2010; Taguchi et al., 2000). Taguchi maintained that it is often possible to achieve robustness by identifying a set of optimum design parameter settings (within a DoE framework) if the environmental noise can be experimentally simulated in an experiment (Roy, 2010; Taguchi, 1986; Taguchi et al., 2000). Taguchi defined robustness as “the state where the technology, product, or process performance is minimally sensitive to factors causing variability (either in the manufacturing or user’s environment) and aging at the lowest unit manufacturing cost” (Taguchi et al., 2000).

While the objective of Taguchi methods (the exact meaning of the term Taguchi methods is discussed later) is to achieve robustness (e.g. reduce variability, reduce defects, achieve consistency in performance), because the response is a measured variable in most of the RD applications, it appears from the literature (e.g. Ross, 1996; Roy, 2010; Taguchi, 1986; Taguchi et al., 2000) that most applications of Taguchi methods revolve around reducing the variability of the quality characteristic of a product (or process) to enable it to stay as close to its target value as possible, under typical operating conditions. In most RD applications the experimenter aims at achieving one of the following objectives:

- i. To maximise the mean response (i.e. the expected value of response), while minimising the variation of the response at the same time; these problems are

known as “larger the better” optimisation problems (Khuri & Mukhopadhyay, 2010; Roy, 2010).

- ii. To minimise the mean response, while minimising the variation of the response at the same time; these problems are known as “smaller the better” problems (Khuri & Mukhopadhyay, 2010; Roy, 2010).
- iii. To minimise the variation (dispersion) of the response and adjusting the mean response to the target value; these problems are known as “target is best” problems (Khuri & Mukhopadhyay, 2010; Roy, 2010).

In addition to handling the above three types of optimisation problems, Taguchi also developed RD methods to develop products whose performance becomes minimally sensitive to “component variation”, and to improve the product and system reliability (Box et al., 1988; Nair et al., 1992; Nalbant, Gökkaya, & Sur, 2007). Coverage of these additional areas is beyond the scope of this research.

In order to review Taguchi methods further, which requires reference to certain terms used in these methods, a frequently cited dataset along with the terminology used in Taguchi methods (data copied from Pignatiello & Ramberg, 1985) are shown in Table 3.1 below. The dataset pertains to a RD experiment designed to determine the optimum design parameter settings (control factor settings) to obtain the target stiffness (with minimum variation) during the heat treatment phase of an automobile leaf spring manufacturing process.

Table 3.1: The Illustrative Example on Taguchi Methods

Control Factors and their Settings				Noise Factors and their Settings					
				Q: Quench oil temperature (°F)					
A: High heat temp (°F)	B: Heating time(s)	C: Transfer time (s)	D: Hold down time (s)	Low (≈140°F)	Low (≈140°F)	Low (≈140°F)	High (≈160°)	High (≈160°F)	High (≈160°F)
1840	23	10	2	7.78	7.78	7.81	7.50	7.25	7.12
1880	23	10	3	8.15	8.18	7.88	7.88	7.88	7.44
1840	25	10	3	7.50	7.56	7.50	7.50	7.56	7.50
1880	25	10	2	7.59	7.56	7.75	7.63	7.75	7.56
1840	23	12	3	7.94	8.00	7.88	7.32	7.44	7.44
1880	23	12	2	7.69	8.09	8.06	7.56	7.69	7.62
1840	25	12	2	7.56	7.62	7.44	7.18	7.18	7.25
1880	25	12	3	7.56	7.81	7.69	7.81	7.50	7.59

└ Inner Array
└ Outer Array
└ Response Data

In general, two types of factors (e.g. see Table 3.1) are being manipulated in RD experiments: the control factors and noise factors. Control factors are defined in the literature as factors that can be controlled in an experimental setting as well in a real process setting to obtain the desired response, while noise factors are defined as factors that cannot be realistically controlled in a real process setting but may be done so during an experiment, usually with some difficulty (Roy, 2010; Taguchi et al., 2000).¹⁴ In the experiment pertaining to the dataset given in Table 3.1 (this experiment has only one noise factor), Pignatiello and Ramberg (1985) report that the engineers adjusted the noise factor “quench oil temperature” with some difficulty.

A salient feature in the RD methodology advocated by Taguchi (i.e. Taguchi methods) is the creation of a cross-array type factorial design by crossing the design array consisting of control factors known as the inner array and with the design array consisting of noise factors known as the outer array (e.g. Table 3.1). Taguchi prescribed *standardised* orthogonal design matrices for the inner and outer arrays for the users to select the orthogonal arrays (inner and outer arrays) that suit their requirements; for ease

¹⁴ This study covers only standard robust designs known as “statistic designs”. There are also designs known as “dynamic designs” where a third type of factor known as the signal factor is involved. Signal factors are used when the actual target remains dynamic (e.g. the temperature setting in a cooling system) (Taguchi et al., 2000). Also within statistic designs, there are situations where it becomes difficult to identify the noise factors. Such situations are handled as standard replicated factorial designs (Taguchi et al., 2000; Wadsworth, Stephens, & Godfrey, 2002).

of reference each different design array was given a specific label: the L4 orthogonal array, the L8 orthogonal array, the L9 orthogonal array, the L12 orthogonal array and so on (Roy, 2010). The cross-array format prescribed by Taguchi ensures that all combinations of control factors (in the example given in Table 3.1 there are 8 combinations of control factors) that are subjected to the exact same combination of noise factors, as evidenced in Table 3.1 (in the example given in Table 3.1 the experimenters have used three replications under the two levels of the noise factor to improve the precision of the estimates). The cross-array structure enables unconfounded interactions between control factors and noise factors, which holds the key in determining a robust factor (parameter) setting (Montgomery, 2013; Roy, 2010). In Taguchi methods, determining the optimum factor settings to achieve the robustness is driven by a performance criterion known as the signal to noise ratio (SNR), which is calculated from the responses for each control factor combination, depending on the objective of the optimisation (Roy, 2010; Taguchi, 1986, 1987). The SNR for a larger the better (SNR_L) experiment, smaller the better (SNR_S) experiment, and target is best (SNR_T) experiment, in an experiment containing n number of runs of the response y ($n = 6$ for the example in Table 3.1) are shown below:

$$SNR_L = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right] \quad (3.1)$$

$$SNR_S = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right] \quad (3.2)$$

$$SNR_T = -10 \log_{10} \left[\frac{S^2}{\bar{y}^2} \right] \quad (3.3)$$

where \bar{y} is the mean response while S^2 is the variance of y .

A two-step optimisation procedure was recommended by Taguchi for target is best experiments (Roy, 2010; Taguchi, 1986, 1987; Wu & Hamada, 2009; Wu & Chyu, 2002). The first step is to maximise the SNR by way of identifying the parameters (control factors) that have the greatest effect on the SNR —the objective being minimising process (product) variability in a manner that does not affect its mean (Phadke, 1982; Roy, 2010; Taguchi, 1986, 1987). The second step is to adjust the mean

response (if required) to the target by way of identifying the so-called “adjustment factors”. The adjustment factors are the specific control factor/s that can be adjusted to bring the mean response towards the target, without affecting the SNR (hence variability) (Roy, 2010; Taguchi et al., 2005; Wu & Chyu, 2002).

A great deal of discussion and peer review on Taguchi methods took place in the so-called “Taguchi era” (1980s through to mid-1990s) once Taguchi and his followers started publishing papers (e.g. Taguchi, 1986, 1987; Taguchi et al., 2005) on Taguchi’s RPD approach for the benefit of the west (Taguchi developed and practiced his methods in Japan). Nair et al. (1992) reported the viewpoints (arguments and counter arguments) of a panel of DoE experts who either supported (fully or partially with suggested refinements to methods prescribed by Taguchi) or opposed Taguchi methods in favour of alternative DoE methods on RD such as the “response surface alternatives” (see Myers et al., 1992 for a seminal paper on the topic). Robinson, Borror, and Myers (2004) succinctly summarised the arguments in Nair et al.’s paper and then covered new developments that have taken place since the said paper. Arvidsson and Gremyr (2008) reported a more up-to-date account of the RD methodology.

As is the case with any two competing methods, Taguchi methods as well as alternative DoE methods on RD that were subsequently advanced will have their own strengths and limitations. It is mentioned in the literature (e.g. Engelhardt, 2001; Karna, Singh, & Sahai, 2012; Tay & Butler, 1999) that the appropriateness of a particular RD method depends on the knowledge and preferences of the quality improvement team as well as other contingency factors. For example, perhaps a team that is well versed in advanced statistical methods may opt for an alternative DoE method (e.g. the response surface alternative to Taguchi methods) to achieve robustness while a team that has a great deal of process knowledge may opt for Taguchi methods (Engelhardt, 2001; Sahoo, Tiwari, & Mileham, 2008b). Proponents of Taguchi methods argue that these methods have gained currency because they are pragmatic (and hence efficient and effective) ways of designing and analysing experiments (Bañuelas & Antony, 2003; Park & Ha, 2005; Phadke, Kackar, Speeney, & Grieco, 1987; Rahman, 1998; Rowlands, Antony, & Knowles, 2000; Roy, 2010). The preceding subsections cover the key debates on Taguchi’s RPD approach.

3.4.2. The Key Debates on Taguchi's RPD Approach

In reviewing the debates on Taguchi's RPD approach, the researcher uses the framework used by Robinson, Borrer and Myers (2004) to identify the domain of Taguchi's RD approach. Robinson et al. viewed Taguchi's RPD approach as an approach consisting of three interlocking elements: Taguchi's Quality Philosophy (including how it is being implemented in practice), Taguchi's teachings on how a RPD experiment should be planned and designed, and Taguchi's data analysis methodology. It is important to note that Taguchi as well as many followers of Taguchi's RPD approach (e.g. Mayer & Benjamin, 1992; Taguchi, 1995; Taguchi et al., 2005) view this approach as a paradigm. The researcher's stance is that if Taguchi's RPD approach is not a paradigm, it has at least the key elements of a paradigm (e.g. an epistemology and a methodology).

3.4.2.1. Taguchi's Quality Philosophy

Taguchi's Quality Philosophy holds that any deviation of the functional characteristic (quality characteristic) of a product from its target value causes an overall loss to society—the loss being proportional to the squared difference between the observed value and the target value (Byrne & Taguchi, 1987; Gunter, 1987; Roy, 2010; Taguchi et al., 2000). Whereas the conventional quality planning and quality control is based on the notion that a capable process is a process that produces products whose quality characteristic stay anywhere within the specified tolerance range (specification limits), nearly all the time, quality planning and control based on Taguchi's RPD approach is based on the notion that variation needs to be minimised by attempting to minimise the loss to society by making the quality characteristic to stay at the target value as close as possible (Gunter, 1987; Roy, 2010; Taguchi et al., 2000).

The loss to society (due to poor quality) concept advanced by Taguchi brought a whole new dimension to cost of quality (Ganeshan, Kulkarni, & Boone, 2001; Omar & Murgan, 2014; Unal & Dean, 1991). Traditionally, cost of quality is considered to be the cost incurred by the manufacturer at the production facility (i.e. up to the point the goods are shipped to the customer) due to costs associated with conformance (e.g. quality control procedures and/or inspection) and nonconformance (e.g. rework, and

scrap) (Dale & Wan, 2002; Rahman, 1998; Schiffauerova & Thomson, 2006). Taguchi takes a more holistic view on poor quality, by considering the losses to the society as a whole forego by not building quality into products in the first place (i.e. design and development stage of the product). Costs associated with rework, waste of resources throughout the supply chain, customer complaints and dissatisfaction associated with various quality dimensions (e.g. durability, reliability, serviceability), warranty costs, losses incurred by the customer on malfunctioning/failing products, tolerance stack up, and numerous non-value adding activities associated with quality assurance are the consequences of not building quality at the design and development stage of the product (Taguchi & Clausing, 1990; Unal & Dean, 1991). By positing loss to society (hence cost of poor quality) as a function of variation through the quadratic loss function, Taguchi provided a simple but a powerful model of process efficiency and effectiveness: lesser the variation lesser the loss and therefore, greater the quality.

Based on prior work (e.g. Box et al., 1988; Nair et al., 1992), it becomes apparent that Taguchi's Quality Philosophy, the first element of Taguchi's RD approach has been accepted as a sound philosophy on quality (more technically, lack of quality), even by the strongest critics of Taguchi. For example, Box et al. (1988) show that Taguchi's Quality Philosophy provides a basis to add the losses forgone by various stakeholders (e.g. the customers, the manufacturing organisation, the wider society) in failing to meet the target value of the quality characteristic and therefore, Taguchi provides a more comprehensive definition on lack of quality (or cost of quality); however they argue that in complex multi-stakeholder situations computation of loss to society becomes very complicated. They also observe that Taguchi's Quality Philosophy (quadratic loss concept) is consistent with his efforts to design experiments that minimise the mean square error (the average of square of the difference between the observed values y and target value T , given the noise profile created in the experiment), although they do not view the *SNR* as an efficient performance criterion to achieve an optimum design (more about this later). It is interesting to note that many scholars (to name a few, Kumar, Chattopadhyaya, & Singh, 2012; Myers et al., 1992; Stone & Veevers, 1994) refer to Taguchi's Quality Philosophy as simply, "Taguchi Philosophy".

Box and his colleagues (e.g. Box, 1988; Box et al., 1988; Box & Jones, 1992b) as well as Montgomery (2009, 2013) and some others (e.g. Myers et al., 1992; Robinson et al., 2004) see objections in the second and third elements of Taguchi's RD approach. At

this stage the researcher would like to be specific by mentioning that what she refers to as *Taguchi methods* in the thesis are these second and third elements of Taguchi's RD approach: Taguchi's prescriptions on planning and designing a RD experiment, and the data analytic methods prescribed by Taguchi. Criticisms levelled at each of the two elements are covered below, using the key citations.

Interestingly, Kackar (1989), one of the proponents of Taguchi's RD approach, provides an extended definition on Taguchi's Quality Philosophy. According to him, Taguchi's Quality Philosophy contains seven basic precepts. These are (as paraphrased):

1. An important dimension of the quality of a manufactured product is the total loss generated by that product to society.
2. In a competitive economy, continuous quality improvement and cost reduction are necessary for staying in business.
3. A continuous quality improvement program includes incessant reduction in the variation of product performance characteristic about their target values.
4. The customer's loss due to a product's performance variation is often approximately proportional to the square of the deviation of the performance characteristic from its target value.
5. The final quality and cost of a manufactured product are determined to a large extent by the engineering designs of the product and its manufacturing processes.
6. A product's (or process') performance variation can be reduced by exploiting the nonlinear effects of the product (or process) parameters on the performance characteristics.
7. Statistically planned experiments can be used to identify the settings of product (and process) parameters that reduce performance variation.

(Kackar, 1989, p. 3-4)

The researcher observes that point 2 of Kackar's extended definition of Taguchi's Quality Philosophy falls very much in-line with Deming's concepts on continuous improvement. The researcher also observes that points 3, 5, 6, and 7 actually reflect

planning and designing experiments. In keeping with the viewpoint of Robinson et al. (2004), the researcher views planning and designing experiments as a resultant aspect of Taguchi's loss to society concept (point 1 above) and quadratic loss (point 4 above). Therefore, in the operationalisation of Taguchi's Quality Philosophy, the researcher considers points 1 and 4 only.

3.4.2.2. Taguchi's Prescriptions on Planning and Designing a RPD Experiment

With regard to the second element of Taguchi's RPD approach (i.e. Taguchi's prescriptions on how a RPD experiment should be planned and designed), Box (1988) argue that Taguchi's prescriptions on planning and designing just one big experiment (which Box calls a "one shot experiment"), instead of a series of smaller experiments, undermines the general DoE principle of gaining knowledge about a phenomenon sequentially (the KISS principle). Box view Taguchi's prescriptions to be very *solution-driven* as opposed to being *discovery driven*; Box and his colleagues also find objections on Taguchi's "cook book" style prescriptions on designing experiments, as these prescriptions give very little explanation as justification (Box, 1988; Box et al., 1988). On a similar line, Montgomery (1999) argues that Taguchi's experimental designs force engineers to become pre-occupied with optimisation (this has also been highlighted by Myers et al., 1992), by-passing the important early phases on knowledge building: "characterisation" (identifying the dominant factors from simple experimental designs) and "control" (making sure during the course of the experiment that the process being examined is statistically in control, when the factor levels are unchanged). On the same token Montgomery (1999, 2009) as well as Box (1988) assert that a great deal of process knowledge is assumed in designing an experiment based on Taguchi's prescriptions when process knowledge can in fact be gained gradually through a series of experiments, allowing statistics to prompt the experimenter as to what seems to be happening in the process being examined.

The researcher's position on the concerns referred to in the previous paragraph is that while it is always good for an engineer to work as a true scientist, making discoveries in a systematic fashion, in practice, she does not always create solutions from scratch. For example, in a product development situation, what an engineer might want to do (as a

part of CI) might be to provide a minor upgrade to an existing product (e.g. say, improve the performance by say 5%, given the technological limitations). In such a situation, the engineer is likely to have gained adequate process knowledge over time (e.g. through the application of the PDCA CI cycle of learning) to design a Taguchi style RPD experiment. Moreover, there could be contextual factors that limit the application of conventional style experiments (that lead to a RPD) that Box, Montgomery and others allude in certain situations. These are things that need to be further investigated in relation to a specific context.

The researcher acknowledges that there are other criticisms on Taguchi style RPD experiments. One such criticism is that these experimental designs focus on optimisation of a single quality characteristic of a product as opposed to the more realistic situation of simultaneous optimisation of multiple quality characteristics (Azadeh, Miri-Nargesi, Goldansaz, & Zoraghi, 2012; Jeyapaul, Shahabudeen, & Krishnaiah, 2005; Park et al., 2006; Su & Tong, 1997). Another criticism is that the inner array of most of the designs become highly fractionalised factorial designs, leaving no flexibility to capture (and hence understand) the interactions among the control factors (Nair et al., 1992; Shoemaker, Tsui, & Wu, 1989). Yet another criticism is that the cross-array structure in the experimental design leads to a “split-plot” type structure (this limits the degree of randomisation possible), which should be handled appropriately using a split-plot style ANOVA (Montgomery & Runger, 2010). A useful inquiry would be to examine to what extent some of the sophisticated statistical methods advocated in alternative DoE approaches become viable in a setting such as apparel production.

3.4.2.3. The Data Analytic Methods Prescribed by Taguchi

Taguchi’s data analytic methods, the third and the final element in Taguchi’s RPD approach, is a very important element because through these methods Taguchi attempted to bring his empirical knowledge on process variation in line with statistical thinking in a pragmatic way (Phadke, 1982; Roy, 2010; Wu & Chyu, 2002). It can be judged from the literature (e.g. Box, 1988; Khuri & Mukhopadhyay, 2010; Myers et al., 1992; Nair et al., 1992; Robinson et al., 2004; Wu & Hamada, 2009) that among all the issues associated with Taguchi methods, the foremost is the use of the *SNR* (in two-

steps) as a data analytic tool to achieve robustness (see section 3.4.1 for the definition of the SNR , in particular SNR_T , and how it is used as data analytic tool to minimise variability around a target value).

Box (1988) critically reviewed the SNR as a performance criterion in the three modes the SNR is mostly associated with: response maximisation, response minimisation, and achieving the target (see the three corresponding SNR equations in section 3.4.1). Box began his argument by observing that in keeping Taguchi's Quality Philosophy it would be more logical to adopt the mean square error (MSE), or still better, $\log(MSE)$ as the performance criterion to be minimised (which is the same as maximising $-\log(MSE)$). The reader should note that the MSE is also referred to as the mean square deviation (MSD) in the literature (e.g. Roy, 2010; Taguchi, 1986, 1987). The MSE (or MSD) is defined as follows.

Supposing if the product's quality characteristic takes the values Y_1, Y_2, \dots, Y_n for a certain fixed control factor setting, when the product is subjected to a certain noise profile n times, and if the desired (target) value of the quality characteristic is T , then MSE (or MSD) is given by:

$$MSE = \frac{\sum_{i=1}^n (Y_i - T)^2}{n} = \frac{(n-1)}{n} s^2 + (\bar{Y} - T)^2 \quad (3.4)$$

Where \bar{Y} and s^2 are the sample mean and variance respectively.

It is interesting to note that some users of Taguchi methods (e.g. Bilici, 2012; Huang, 2015; Oktem, Erzurumlu, & Uzman, 2007; Roy, 2010) actually use $-10\log_{10}(MSE)$ as the preferred SNR (which is to be maximised) for the "target is best" type optimisation problems, thus keeping in line with Box's assertion. However, Taguchi was not in favour of using MSE (or maximising $-\log(MSE)$) as a performance criterion (response) to be maximised in "target is best" optimisation problems, because based on Taguchi's *practical experience*, he found that sometimes, a much lower MSE (and hence a much lower overall loss to society) can be obtained if the variance (s^2) is minimised first by identifying and manipulating the dominant control factors, and then the average (\bar{Y}) is brought to the target (T) next by identifying an adjustment factor and manipulating it, in a two-step fashion (see equation 3.4) (Phadke, 1982; Wu & Chyu, 2002). The main

reason Taguchi gives for not favouring minimising MSE in one attempt is the presence of interactions between control factors on some occasions (Phadke, 1982; Wu & Chyu, 2002).

Using mathematical explanations, Box (1988) showed the SNR_T performance criterion, the criterion that Taguchi prescribed to achieve minimum variability around the target (see equation 3.3), is statistically *inefficient*, in general; the term statistical inefficiency was used by Box to mean loss of some information conveyed in the data. Box showed that SNR_T becomes efficient if and only if the mean (\bar{Y}) and the standard deviation (s) are linearly related, in which case, SNR_T becomes a “Performance Measure Independent of Adjustment” (abbreviated as PerMIA in the literature) (Box, 1988; León, Shoemaker, & Kacker, 1987). In other words, under the $s \propto \bar{Y}$ condition, maximisation of the SNR_T would minimise the standard deviation s , without affecting \bar{Y} , which is the first step in Taguchi’s two-step approach (in the second stage, the MSE would be further reduced by moving \bar{Y} towards the target, using the adjustment factor/s). (Phadke, 1982) note that Taguchi observed practically anyway that on many occasions (\bar{Y}) and the standard deviation (s) are linearly related and that this why he uses SNR_T to combine to two parameters \bar{Y} and s into a single parameter on variability.

Box also showed that the other two SNRs that Taguchi prescribed, SNR_L and SNR_S for response maximisation and minimisation respectively, are also statistically inefficient, in general. Box argued that, data analytic methods such as the “lambda plots” are more efficient than the SNR in removing the functional dependence of mean (\bar{Y}) and the standard deviation (s) to minimise the MSE (i.e. minimise the loss to society). The next section reviews an alternative approach to achieve robustness. This approach, known as the “response surface alternative to Taguchi’s robust parameter design approach” (Myers et al., 1992) or simply the “response surface approach to robust parameter design” (Khuri & Mukhopadhyay, 2010) does not involve the standard accessories such as cross-arrays and SNRs that Taguchi prescribed.

3.4.3. The Response Surface Alternatives to Taguchi's Robust Parameter Design Approach

Two influential papers appeared in 1990—Box and Jones (1992a) and Vining and Myers (1990)—showing how response surface methodologies could be used to achieve robustness. At the same time, a paper was published by Welch, Yu, Kang, and Sacks (1990) showing how Taguchi's inner array and outer array could be combined into a single array to achieve economy (lesser number of runs) in achieving robustness within a robust parameter design framework. Few years later Myers, Khuri, and Vining (1992) incorporated the work of the above and other papers to package response surface methods involving single arrays (known as combined-arrays) as an attractive alternative to Taguchi's RD approach. Latest publications (e.g. Khuri & Mukhopadhyay, 2010; Montgomery, 2009, 2013; Wu & Hamada, 2009) show that statisticians continue to favour these response surface alternatives over Taguchi methods for planning and designing experiments as well as analysing the data.

Myers, Khuri, and Vining (1992) assert that the response surface alternatives offer three main benefits. This first main benefit they show in response surface alternatives is the *economy*, meaning requiring lesser number of runs compared to Taguchi methods. Using an illustrative example involving 3 *control factors* and 2 *noise factors* they show that a 5-factor composite design consisting of a single array can fit response surface models for mean and variance from just 22 experimental runs (16 factorial runs from the 2^{5-1} fractional factorial design and 6 axial runs at ± 1 coded units along the axes of the three control factors) and a few centre point runs (the centre point runs are required to estimate the pure error) to achieve robustness by minimising the variance and bringing the mean to the target. The second main benefit of response surface alternatives that Myers et al. (1992) show is incorporation of a *modelling strategy*. That is, being able to fit models that predict the mean and variance of the quality characteristic, given the noise factors considered. The third main benefit of response surface alternatives that Myers et al. (1992) show is being able to explore the region that contains the optimum solution to learn more about the process. They also show that response surface alternatives on robust designs also fit the sequential learning strategy (KISS principle) advocated in conventional DoE methods very well.

It appears that the *single response approach* introduced by Box and Jones (1992a) is a popular response surface alternative in the current literature (e.g. Montgomery, 2013). In the single response approach the researcher fits a single model to estimate response of interest as a function of the control factors and noise factors including the two-way interactions between control factors and noise factors as well as between the control factors themselves. In this approach the noise factors are treated as fixed effects. This generic model is then used to predict the expected value of response (i.e. the mean response) and the variance of the response making certain assumptions (the researcher used the single response approach in her study). The alternative response surface approach to RPD is the *dual response approach* where separate models are fitted for mean and the variance (Khuri & Mukhopadhyay, 2010).

It is clear that the response surface alternatives on RPD also share Taguchi's Quality Philosophy, in that the aim of these experiments are also to reduce the variability of the product's functional characteristic around its target value (i.e. to achieve robustness). However, the response surface alternatives (the single or dual response approaches) depart from Taguchi's RPD approach considerably in planning and designing the experiments (e.g. Taguchi's cross-array approach is not used) as well as the data analytic methods (e.g. the signal to noise ratio prescribed by Taguchi is not used, a modelling strategy is used to further examine the optimum region).

3.4.4. Application of Taguchi Methods in the Industry

3.4.4.1. General Applications

Taguchi methods have been applied in many manufacturing and service industries for the purpose of finding controllable factor settings that are most important in achieving product (or process) robustness (Azadeh et al., 2012; Rowlands et al., 2000). While publications covering the debates on the merits and demerits of Taguchi methods were prevalent in the "Taguchi era", namely 1980s to mid-1990s, the current trend seems to be to get on with Taguchi methods by applying it to get results.¹⁵ Consequently there are a large number of case study examples on the application of Taguchi methods in

15 This claim is made on the basis of article search (number by publications by year via the article database Scopus from 1984-2014 containing the search word "Taguchi Methods" in the article title or abstract or key words (also see Figure 1.1 in Chapter 1).

various sectors such as automotive, electronics and semiconductor, biomechanical engineering, material science, chemical process, and food. A few of these are described below to provide a general flavour on the application of Taguchi methods.

Using the SNR_S performance criterion and other related experimental planning and data analysis methods associated with Taguchi methods, Oktem, Erzurumlu, and Uzman (2007) minimised the variability of warpage and shrinkage associated with a plastic injection moulding process. The robust parameter setting that they found enabled them to improve (reduce) the baseline values (i.e. process performance prior to the RD) by about 2.17% and 0.7% of warpage and shrinkage respectively. Yang and Tarn (1998) as well as Nalbant, et al. (2007) applied Taguchi methods to determine the optimal cutting parameter settings to minimise surface roughness in "turning" operations. In both studies, substantial improvements were recorded. For example, in first study (the study by Yang and Tarn), which was designed to maximise tool life (here the SNR_L was involved) and minimise the surface roughness (here the SNR_S was involved), the experimenters were able to improve the baseline performance by about 250% for both tool life and surface roughness. Similarly, Zhang, Chen, and Kirby (2007) optimised surface roughness in an end-milling operation using the Taguchi methods. Their experiment contained three controllable factors (each set at three levels) and two noise factors (each set at two levels) and the cross-array consisted of 36 experimental runs. The results that the experimenters obtained as well as their on-field experience prompted them to claim that Taguchi methods are efficient and effective in optimising surface roughness in milling operations.

3.4.4.2. Fashion Industry Applications

Apparel manufacturing belongs to the fashion industry. Application of Taguchi methods in the apparel industry is quite new (Mavruz & Ogulata, 2010). Park and Ha (2005) used Taguchi methods to optimise the sewing conditions to reduce the "seam pucker" using four control factors: sewing speed, stitch length, needle tread tension, and presser foot pressure. Mavruz and Ogulata (2010) used Taguchi methods to optimise the bursting strength of knitted fabric using certain yarn and fabric parameters as control factors.

Yoon et al., (2010) applied Taguchi methods to enhance the quality of clothing production. Their study focused mainly on optimising the fusing conditions to maximise the bonding strength between fabric and fusible interlining. The cross-array used by the experimenters consisted of four control factors (type of fusible interlining, fusing temperature, pressure, and time), each set at three levels as an L9 orthogonal array, replicated 6 times. The fact that the outer array contained no noise factors suggests that the experimenters were not able to identify specific noise factors. It appears that the experimenters have simply used 6 replicates of the 9 factor combinations in the L9 inner array in order to adequately represent the noise the process is subjected to. Consequently the cross-array design consisted of 54 (= 9×6) experimental runs. The experimenters used larger the better SNR (i.e. SNR_L) in the data analysis as they were seeking maximisation of the quality characteristic (bonding strength). The experimenters achieved a bonding strength that was 18.2 times higher than the baseline bonding strength. They concluded that robust parameter settings that maximise the bonding strength (with minimum variability) were easily determined using the simple and easy to understand prescriptions in Taguchi methods.

3.4.4.3. Application of Taguchi Methods in Lean Environments

Some researchers have used Taguchi methods in Lean environments to improve operational performance. The key applications are covered in this section. However, the researcher notes that there has not been a single comprehensive study that examined to what extent Taguchi's RPD approach fits with Lean manufacturing. As the researcher has referred to in section 3.4.2, Taguchi's RPD approach consists of three interlocking elements (Taguchi's Quality Philosophy, Taguchi's teachings on how a RPD experiment should be planned and designed, and Taguchi's data analysis methodology). Therefore any comprehensive study that involves Taguchi's RPD approach should cover how all three elements fit (or otherwise) in a Lean environment.

Sahoo, Singh, Shankar, and Tiwari (2008a) used Taguchi methods to minimise forging defects produced due to imperfect (and unavoidable) operating conditions (noise) in a Lean production facility. Sahoo et al. used Taguchi method in conjunction with the *DMAIC* problem solving process used in Six Sigma. The inner array used by the experimenters consisted of five control factors (each set at three levels) associated with

radial forging. The outer array used by them represented 5 replicates run at each factor combination of the inner array; this again implies that the experimenters were not able to identify specific noise factors and they simply used the replicates to adequately represent the noise the process is subjected to. Having picked the optimum factor combination based on the SNR_S , Sahoo et al. used the response surface methodology to further adjust (trim) the parameter settings.

Moeeni, Sanchez, and Ria (1997) used Taguchi methods to optimise a Kanban system of a 3-stage production process in a JIT (Lean) production environment. While Moeeni et al. achieved a robust parameter setting, they suggested that further investigations need to be done to determine whether a SNR based on a loss function other than the quadratic loss function (as mentioned previously the SNR s used in Taguchi methods are typically based upon the quadratic loss function) could yield a more robust setting.

Chen, Li, and Shady (2010) used Taguchi methods to determine the optimal machining parameter settings to achieve robustness in a plasma cutting process, as part of a kaizen event (a CI event) in a Lean manufacturing organisation. The experimenters used Taguchi methods to solve a dual response problem: minimising the processing time (response 1) and increasing the quality of the product (response 2).

Noorwali (2013) showed how Lean principles and computer simulated statistically designed experiments based on Taguchi's orthogonal arrays can be used to reduce waste and improve performance (e.g. minimise mean % waiting) in a food processing setting. Based on the literature, Noorwali explained how the five Lean principles of Womack and Jones (2003) can be used to reduce waste (see section 2.2.1 for Lean) in a food processing plant. Noorwali also explained how a computer simulated noise profile (i.e. multiple replicated runs being simulated using computer generated noise) is used on a L_{27} orthogonal array (inner array) consisting of six control factors manipulated at three levels. The quality characteristics Noorwali considered for the simulated process were % waiting, % blocking, % stoppages, and % working. Presumably, Noorwali's experiment would have fell short of achieving robustness in the process, in the sense, the experiment that they designed was merely a standard fractional factorial design aimed at reducing the mean times of the 4 responses (there was no variation reduction objective as such). The spirit of Taguchi methods is not to facilitate fractional factorial

designs but to facilitate designing experiments and analysing data, in order to make processes robust against the noise created by the environmental factors.

3.4.4.4. RD Implementation Issues in the Industry

The literature shows that while RD (Taguchi methods and other DoE based methods) is used in the industry in isolation to achieve quality improvement, in most industries, RD is not being recognised as an integral part of product design globally (Araujo, Benedetto-Neto, Campello, Segre, & Wright 1996; Krogstie, Ebro, & Howard, 2014; Thornton, Donnely, & Ertan, 2000). In this section, the researcher reviews the literature pertaining to implementation issues of RD in the industry.

Rowland, Antony, and Knowles (2000) reviewed six RD implementation cases studied by postgraduate researchers in a higher education institute in the UK. They observed that the firms that they reviewed have treated RD experiments in isolation (that is, treating a specific RD experiment as a standalone quality improvement project), without integrating RD as an organisational strategy to achieve quality excellence. They contend that this is the main reason why industries in general have not been able to gain the full benefit of RD. Rowland et al. argue that successful implementation of the RD approach (Taguchi methods), as an organisational strategy, requires a repertoire of organisational competencies—planning skills, engineering skills, communication skills, and teamwork skills—in a culture that promotes active participation and commitment to quality. They also argue that RD tools need to be used in conjunction with the organisation's standard continuous improvement tools and techniques to gain greater acceptance of the RD methodology.

Gremyr, Arvidsson, and Johansson (2003) conducted a survey involving a sample of Swedish manufacturing firms ($n = 87$) to ascertain the viewpoints of manufacturing firms on conformance (to specifications) and RD methodologies. Gremyr et al found that majority of the firms view quality by design as being more important than quality by inspection, although their survey did not capture how each firm archives conformance. Gremyr et al also found that out of the 87 firms that they surveyed, only 24 (28%) have heard about RD methodologies and more disappointingly, of these on 24 firms, only 15 (mostly large companies) actually used them, to a greater-or-lesser extent. The researchers found that majority of the respondents (exact figures have not

been given) disagreed with the researchers' notions that RD methodologies decrease the cost of product development and having dissatisfied customers (due to poor product quality) should motivate a firm to use RD methodologies. Whilst these results do not show what hinders adaptation of RD methodologies, the researchers speculated that unawareness of the overall approach of RD could be the reason as to why RD methodologies are seldom used in the Swedish manufacturing industry.

Through a problem solving case study (the problem being minimising acoustic noise emanating from a particular design of a domestic refrigerator), Gremyr and Hasenkamp (2011) studied how a manufacturer renowned for using RD methodologies to design, develop, and manufacture consumer goods, actually uses RD principles, practices and tools to achieve robustness. Through document inspection, the researchers found that the manufacturer's operational definition of robustness is consistent with Taguchi's definition of robustness, and as expected, DoE is being used as the primary practice to achieve product robustness. The researchers also found that although the engineers developed a relations diagram to understand the potential factors that cause the problem (excessive acoustic noise), in designing the experiment, they overlooked the noise factors, in spite of identifying some of them through the relations diagram. In effect, what the engineers pursued was optimum design parameters (control factor settings) that minimise the mean response (acoustic noise), through a fractional factorial design. Gremyr and Hasenkamp observe that non-incorporation of noise factors in the experimental design either directly (e.g. as factors in the outer array) or indirectly (e.g. as replicated designs) results in a suboptimal robust design, because the experimenter does not use variance minimisation as an objective in the experimental design. Based on this example and analysis of other quality improvement studies in the company (through document inspection), the researchers concluded the RD principles have not permeated in the quality improvement work systems of the company.

Krogstie, et al. (2014) studied four different companies in Northern Europe to understand what motivates companies to adopt RD methodologies and what (factors) contribute towards successful implementation of these methodologies. They found that motivating factor/s for adaptation of RD methodologies in general, differed from one company to another. In company 1 (pharmaceutical manufacturing) the motivation to recourse to RD was to expedite product design and the predictable lead-time; in company 2 (defence equipment manufacturing) it was poor cost of poor quality and tie-

up of resources on inspection and other on-line quality control procedures; in company 3 (aero) it was cost of poor quality, expensive in-service changes, and cost of redesign; in company 4 (auto) again it was cost of poor quality, cost of market failure, and maintaining brand image. The researchers found that each company faced its own barrier to sustain RD methodologies. In company 1 it was resistance to change and employees seeing RD as an additional burden on existing product development activities; in company 2 it was lack of adaptation of RD tools and employees' prior experience on unsuccessful DoE projects; in company 3 it was lack of novelty and over-formalisation of RD processes; in company 4 it was the "tool-pushing" adopted by the external consultants (employees viewed this as being ineffective) and non-recognition of need for change. Krogstie, et al. found that in all 4 companies, staff training has been the primary success factor in overcoming the challenges faced by these companies, in implementing and sustaining RD methodologies. Based on these observations, the researchers concluded that "RD implementation is context dependent" (i.e. factors that motivate them to use RD depend on the context) and that staff training and top-management commitment are the key to implementing and sustaining RD methodologies in manufacturing firms.

Using a Swedish automotive manufacturer (Volvo) as a case study, Mashhadi, Alänge, and Roos (2012) studied what hinders an automotive manufacturer to overlook RD as a primary product/process improvement approach. They found that "tool pushing" approach adopted by the external consultant was the main obstacle (they also found five other obstacles) for RD to gain traction in the organisation. The researchers assert that RD initiatives should originate from the internal staff (most importantly from the engineers) and the organisation must create a learning culture that supports RD principles. Interestingly, the researchers found that the six obstacles that they identified are typical in most organisational change initiatives on quality. This implies that organisations aspiring to implement RD methodologies as well as organisations that have already implemented RD methodologies can benefit by studying successful change management initiatives of the past.

Noesis Solutions (2015), a Belgian based external consultancy organisation specialised in design optimisation (automotive/aero etc.) contend that simulation and virtual prototyping is taking precedence over conventional robust design experiments in the automotive industry due to pressure to lower "time to market". They argue that

simulation-driven robustness assessment techniques, which circumvent conducting physical DoEs, generate useful information on vehicle design parameters for performance, durability and safety more efficiently and effectively, reducing development costs and product development lead-times. Thus, it seems that studying the suitability of Taguchi's RD approach (or the response surface alternative) to a particular industry should take into account the developments in the macro environment, such as the developments in the technological environment and market environment.

3.5. DESIGN FOR SIX SIGMA AND ALTERNATIVE RPD APPROACHES

In the previous chapter (section 2.3.5) the researcher introduced Six Sigma as an approach primarily aimed at reducing variability. Design for Six Sigma (DFSS) is viewed in the literature as incorporation of RPD within a six sigma framework (Bañuelas & Antony, 2003; Chowdhury, 2003; Koch, Yang, & Gu, 2004). Section 3.5.1 provides a synopsis of DFSS to ascertain whether DFSS can be distinguished from integrating Taguchi's RPD approach within a Lean environment. Section 3.5.2 briefly covers alternative RPD approaches.

3.5.1. Design for Six Sigma

Design for Six Sigma (DFSS) is a product/process design approach that incorporates Six Sigma methodologies at the product development stage or product redesign stage to achieve Six Sigma level quality performance (Fouquet, 2007; Kwak & Anbari, 2006). Fouquet (2007, p. 25) defines DFSS as "a means of developing, or improving, products that enables Six Sigma levels of performance in production, while focusing on customer satisfaction and robustness."

In the literature (e.g. Bañuelas & Antony, 2003; Chowdhury, 2003; He, Tang, & Chang, 2010; Mader, 2002) DFSS is seen as a natural extension of Six Sigma when organisations realised that application of Six Sigma methodologies to improve existing processes do not improve quality performance (at best) beyond 5 sigma level (equivalent to a DPMO count of 230, which is much higher than the corresponding DPMO count of 3.4 for a Six Sigma level quality performance), thus requiring either a completely redesigned processes or a new process at the design and development stage

of a product. General electric has been credited with the invention of the DFSS approach; they used DFSS to design and develop a high quality scanner to reduce warranty claims and enhance customer satisfaction by proving a high performance product (better image quality, fast scanning, and high reliability) to compete with major players such as Toshiba and Siemens (Bañuelas & Antony, 2003).

While DMAIC (section 2.3.5) is the sequence through which quality improvement takes place in an existing process in a Six Sigma project, the sequence changes to Design, Measure, Analyse, Develop, and Verify (DMADV) in DFSS (Bañuelas & Antony, 2003; Chowdhury, 2003; Conger, 2015; Cronemyr, 2007). The final step “verify” seems to stand analogous to the very important design verification and validation aspect in product development.

According to the literature, the major distinction between Six Sigma and DFSS is that while the former pays attention to reducing variability via *on line quality control* (i.e. measuring the variability of an existing process through an SPC tool, and then taking steps to reduce it through a quality improvement technique such as DoE) the latter pays attention to reducing variability via *off-line quality control* by building quality dimensions such as *robustness* at the design and development stages of a product (Bañuelas & Antony, 2003; Kovach, Stringfellow, Turner, & Cho, 2005; Mader, 2002). However, the researcher does not view Taguchi’s RPD (or RD) approach to be identical to DFSS. As alluded by the author earlier (section 3.4.2), Taguchi’s RPD approach is almost a paradigm on building quality into products while DFSS is a commercial package on quality improvement that uses robust parameter design principles and other principles on building quality at the design stage of a product. Besides, robustness might not be the only product quality dimension the customer is interested (DFSS looks at other dimensions also).

Fouquet (2007) compared DFSS and Lean Product Development (LPD) to identify similarities dissimilarities of the two product development approaches. Fouquet found inclusion of customer voice at the design stage, cross functional teams, and employee involvement as the elements that are common in both approaches. Fouquet also argued that the visual management system used in LPD can be integrated with DFSS to enable the participants of a DFSS project to visualise and track each step of the product design and development process. As a key difference between the two approaches, Fouquet

found that while DFSS focuses on measuring and attaining customer satisfaction, LPD focuses on CI activities to standardise the existing process. Fouquet went on to argue that DFSS is driven by the application of statistical tools whereas LPD is driven by the application of the so-called “Lean tools”, such as JIT, 5S, workstation standardisation, takt time, visual management, group work, and cross-functional teams to improve quality. The researchers position is that introduction of integrating Taguchi’s RPD approach within a Lean environment does not necessarily equate to introducing DFSS in a Lean environment.

3.5.2. Alternative Robust Design Approaches

Adjusting parameters via an experiment to achieve robustness (i.e. RPD), using Taguchi methods or otherwise is not the only way robustness can be achieved in products and processes (Montgomery, 2013). Deming (2000) prescribed in his management principles that reducing the number of suppliers for a process is an imperative in decreasing the variation in the process (Shin, Collier, & Wilson, 2000) and this is a key responsibility of the management (Anderson et al., 1994). Therefore supplier selection, monitoring and management are important in achieving a robust design.

As mentioned earlier, robustness or variation reduction can also be achieved by effecting major process changes by introducing new technology to prevent variation transmitted from uncontrollable factors such as human factors, machine aging, and various user conditions.¹⁶ In addition, using expensive materials with tight tolerances or high grade raw materials or component parts is another way to reduce the variation transmitted from raw materials or product components to the final product quality (Taguchi et al., 2005). Another invariably expensive approach to a robust design is buffering against uncertainty or unknown using safety factors. This approach usually results in an overdesigned the product, and therefore it is inefficient (Dalton, Atamturktur, Farajpour, & Juang, 2013; Koch et al., 2004).

¹⁶ The researcher does not suggest that new technology is not necessary. New technology is part of innovation and besides, robust design is not the only aspect in production. New technology can increase productivity immensely and therefore it could, in fact, be a source of competitive advantage. What the researcher is implying is that if it is possible to achieve robustness by adjusting the parameters of an existing process, this should be the first choice because it is inexpensive.

In summary, generally speaking, most of the methods covered in this section on QbD are expensive and inefficient (supplier management is an exception) relative to the RPD approaches (Taguchi based DoE or otherwise). Therefore these approaches could be cost prohibitive in today's context where several manufactures have to compete globally under lower profit margin ratios.

3.6. KNOWLEDGE GAPS AND RESEARCH QUESTIONS

In this section, the researcher exploits certain key topics and themes that were covered in the two literature review chapters, the preceding chapter (Chapter 2) and this chapter to frame the research questions. The connections between the key topics, themes, key references and research questions are depicted in Figure 3.2. The links in Figure 3.2 along with the research questions are covered in the next two subsections.

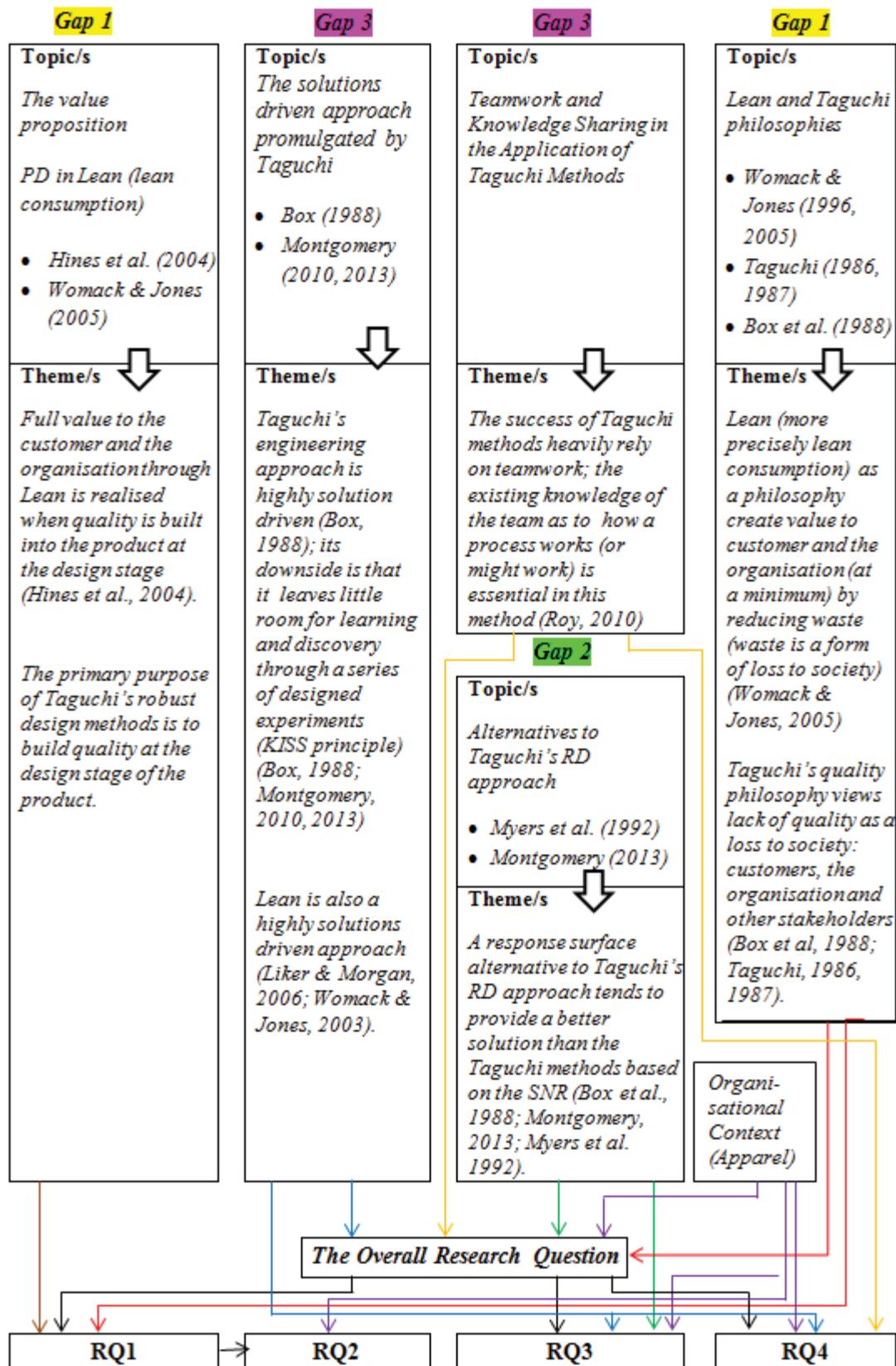


Figure 3.2: Key topics, themes and key references leading to research questions

3.6.1. Knowledge Gaps Identified for the Study

3.6.1.1. Knowledge Gap 1

Section 3.4.2 uncovered that Taguchi's RPD approach consists of three interlocking elements: Taguchi's Quality Philosophy, Taguchi's teachings on how a RPD experiment should be planned and designed, and Taguchi's data analysis methodology (Robinson et al., 2004). The first element, Taguchi's Quality Philosophy was shown to be the key because the other two elements, which belong to the umbrella term *Taguchi methods*, actually pivot on the Taguchi's Quality Philosophy. For example, it was shown in section 3.4.2.3 that the metric *SNR*, the most salient feature in Taguchi methods, and arguably the most researched topic on Taguchi methods, pivots on Taguchi's Quality Philosophy (Rahman, 1998; Roy, 2010; Taguchi et al., 2005). In section 3.4.2.1 it was shown that Taguchi's Quality Philosophy views lack of quality (high variation and deviation of the mean from the target under normal operating conditions) as *a loss to society* (Box et al., 1988; Taguchi, 1986, 1987). Taguchi methods are the means that Taguchi prescribed to engineers to reduce loss to society due to lack of quality by building quality into products in the design and development stage (statisticians of course have recommended alternative methods and one key method was covered in section 3.4.3).

Section 2.2 from the previous chapter uncovered that Lean philosophy is a production philosophy aimed at creating customer value by eliminating waste and non-value adding activities from all possible activities in the value chain. Section 2.2.1 analysed the constituents of the Lean philosophy (the researcher is using the terms Lean thinking and Lean philosophy interchangeably) (e.g. Womack & Jones, 2005a) and it was uncovered that although the primary aim of Lean is CI of operational performance to add value to the customer and the organisation (by reducing waste), it is possible to build additional value (see Figure 2.2) through Lean at the design stage of the product, through superior product quality (e.g. Hines et al., 2004). This idea is consistent with Taguchi's Quality Philosophy (details in section 3.4.2.1).

Section 3.4.4 in this chapter covered different applications of Taguchi methods in the industry, particularly in conjunction with Lean tools within and outside apparel manufacturing contexts. All these studies are piece meal applications of Taguchi's

robust design approach (more specifically, Taguchi methods). The literature lacks a comprehensive study that looks at how two seemingly synergistic philosophies, Taguchi's Quality Philosophy and Lean relate to one another at the theoretical level in explaining improved operational performance. This gap is bridged through the first two research questions: RQ1 and RQ2 (section 3.6.2).

3.6.1.2. Knowledge Gap 2

In section 3.4.3 the response surface alternatives to Taguchi methods were reviewed. It was found that leading statisticians (e.g. Box et al., 1988; Montgomery, 2013; Myers et al., 1992) contend that these alternative DoE methods have the potential to provide better solutions. However, in making the assertions, the statisticians have only considered the statistical merits (e.g. the statistical efficiency). What benefit (if any) the response surface alternatives serve over Taguchi methods in a mature Lean apparel manufacturing context remains unanswered. This gap is bridged through the third research question RQ3 (section 3.6.2).

3.6.1.3. Knowledge Gap 3

If Taguchi methods can build additional value in Lean then it makes sense to understand what drives and what inhibits the uptake of Taguchi methods, given the context of the study (Lean apparel manufacturing). This is more so because Taguchi's RPD approach is viewed as a solutions driven approach in the literature (section 3.4.2.2) and so is Lean (as covered in section 2.2.3, problem solving is a key element in Lean), thus implying synergy between the two approaches from an applications front also.

Unfortunately, the literature also lacks a case study that looks at issues that do arise when Taguchi's RPD approach (more technically, Taguchi methods) is introduced in a Lean context, as a change management intervention. This gap is bridged through the fourth and final research question RQ4 (section 3.6.2).

3.6.2. Research Questions

The research questions that stem from the three knowledge gaps shown in the previous section (section 3.6.1) are as follows.

In section 3.6.1.1 (Knowledge Gap 1) the researcher showed that the literature lacks a comprehensive study that looks at how two seemingly synergistic philosophies, Taguchi's Quality Philosophy and Lean relate to one another at theoretical level in explaining improved operational performance. Thus the first research question is stated as follows.

If the building block of Taguchi's robust parameter design approach, namely Taguchi's Quality Philosophy, is aimed at reducing loss/waste and if Lean is a management system that primarily aims at improving operational performance by reducing waste, the first research question is that:

RQ1 How does Taguchi's Quality Philosophy theoretically relate to Lean, in improving the operational performance?

Once a theory is posited by answering RQ1, then the next step would be to test it empirically for generalisation. When the theory is tested in a Lean apparel manufacturing environment that is not familiar with Taguchi's RPD approach, if effect, one is testing only the acceptance of Taguchi's Quality Philosophy by the practitioners of Lean philosophy in the apparel industry.

Given the theoretical framework within which Taguchi's Quality Philosophy relates to Lean, Thus the second research question is stated as follows.

RQ2 What is the acceptance of Taguchi's Quality Philosophy by the practitioners of Lean philosophy in the apparel industry?

Knowledge gap 2 (section 3.6.1.2) is about wanting to know how two competing RPD methods stand against one another in a mature Lean apparel environment (the context of the study). If Taguchi's Quality Philosophy is related to Lean and if it is accepted as a viable paradigm by Lean practitioners in the apparel industry, thus the third research question is stated as follows.

RQ3 What are the statistical and operational merits and demerits (if any) of using Taguchi methods over conventional robust design experimental methods in solving important quality problems in apparel manufacturing?

The third research question RQ3 has both a practical (operational) element as well as a technical (statistical) element on Taguchi methods, relative to the response surface alternative. The practical (operational) element of RQ 3 can be re-framed as follows:

RQ3a: Which robust parameter design experimental planning method suits the practitioners in mature Lean organisations in apparel manufacturing: the Taguchi method or the response surface alternative?

The technical element of RQ 3 can be re-framed as follows:

RQ3b: Which data analytic method suits the practitioners in mature Lean organisations in apparel manufacturing: the statistical tools prescribed in Taguchi methods or the ones used in the response surface alternative?

Knowledge gap 3 (section 3.6.1.3) is about wanting to know what drives and what inhibits the uptake of Taguchi methods in Lean apparel manufacturing. Thus the fourth research question is stated as follows.

RQ4 What drivers and what restraints do apply when Taguchi methods are actually being introduced in a mature Lean environment in the apparel industry?

The overall research question that encapsulates the four research questions can be stated as follows.

Does Taguchi's RPD approach (Taguchi's Quality Philosophy and the DoE methodology prescribed by Taguchi) appear to be a complimentary approach in a mature Lean apparel manufacturing environment to enhance Manufacturing Process Outcomes?

3.7. CHAPTER CONCLUSION

A substantial portion of this chapter is dedicated to review of the literature on robust parameter design (RPD) approach and design of experiments, the wider context of the RPD approach (section 3.4). This section was divided into four sub sections: Taguchi's RPD approach (section 3.4.1), the key debates on Taguchi's RPD approach (section

3.4.2), the response surface alternatives to Taguchi's RPD approach (section 3.4.3), and application of Taguchi methods (section 3.4.4).

Through the literature review (section 3.4.2), it was found that Taguchi's RPD approach consists of three interlocking elements: Taguchi's Quality Philosophy (section 3.4.2.1), Taguchi's prescriptions on planning and designing a RD experiment (section 3.4.2.2), and Taguchi's data analytic methods (section 3.4.2.3). The researcher showed that although the alternative RPD approaches (specifically the response surface alternatives) *also share Taguchi's Quality Philosophy* (see section 3.4.3), these response surface alternatives depart from Taguchi's RPD approach considerably, with regard to the other two elements of Taguchi's RPD approach (these two elements are collectively known as Taguchi methods).

The researcher showed (section 3.4.4) that the literature lacks a comprehensive study (within or outside apparel manufacturing) that looks at how two seemingly synergistic philosophies, Taguchi's Quality Philosophy and Lean relate to one another at the theoretical level in explaining improved operational performance. This was the basis for the first two research questions of the study (also see section 3.6). As shown in the literature review, implementing Taguchi methods is a simple and less costly strategy of achieving robustness in the products and processes (hence quality). The basis of the third research question was to examine how the two competing RPD methods that share the same philosophy on quality, namely Taguchi methods and response surface alternatives stack against one another in a mature Lean apparel manufacturing context. The basis of the fourth research question was the practical implementation of Taguchi methods.

The researcher also reviewed DFSS (section 3.5.1) because DFSS has some parallels with RPD in a Lean context. The researcher showed that DFSS comes close to integrating Taguchi's RPD approach in a Lean context. However, researcher contended that they are not exactly the same.

In the next chapter (Chapter 4) the researcher describes the methodology that was adopted in answering the first two research questions.

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CHAPTER 4

THE RESEARCH PARADIGM, EMPIRICAL MODEL BUILDING AND DATA COLLECTION

“Essentially, all models are wrong, but some are useful.”

—George Box

4.1. INTRODUCTION

This chapter is the first of the two chapters that cover the methodology of the study. This chapter is used to design the methodology to achieve the first research objective: to formulate and statistically test a theory that predicts and explains how *Taguchi’s Quality Philosophy* and *Lean* management jointly contribute towards improving the operational performance in a mature Lean apparel manufacturing environment. In achieving the said research objective, the researcher answers her first two research questions (see section 3.6.2). The chapter begins (section 4.2) with a review of dominant research paradigms available for conducting social science research and the justification of the particular paradigm chosen by the researcher: the *postpositivistic paradigm*. The justification of the research paradigm is followed by the theoretical model development (the model hypothesising the relationships between Taguchi’s Quality Philosophy and Lean Manufacturing System via the mediating variable Continuous Improvement (CI), to achieve Manufacturing Process Outcomes) through an extensive literature review (section 4.3). The model (Figure 4.1) consists of six interrelated hypotheses involving four constructs. The next section (section 4.4) describes the development of the operational definitions for the four constructs of the model, in the form of a *survey questionnaire* (the questionnaire is shown in Appendix A). Section 4.5 covers the sampling frame, the respondents on whom the questionnaire was administered upon, as well as the other details of data collection. Section 4.6 covers the methods and strategies that were used in testing the reliability and validity of the measurement system. The assumptions used in the *model testing is part of the study* (i.e. assumptions relevant to that part of the methodology that is covered in this chapter) are also covered in section 4.6. Finally, section 4.7 concludes

this chapter with a summary on the methodology used to develop and test the theoretical model.

4.2. RESEARCH PARADIGMS

The researcher's study involves a Lean Manufacturing System, which consists of people, knowledge, methods, and capital to achieve certain goals. The people in the system are not passive objects because their behaviour is something that is known to have varied within organisations and cultures, historically (Somekh, Burman, Delamont, Meyer, Payne, & Thrope, 2011). The researcher's research questions and objectives include inquires of social nature such as finding out the acceptability of Taguchi's Quality Philosophy by the practitioners of Lean in the apparel industry. As such the researcher's study falls into the social science discipline. The question then is how to state "knowledge claims" (Creswell, 2014)—often known as the paradigms (Kuhn, 1962; Lincoln & Guba, 2000)—in social science?

According to Creswell (2014, p. 6), a paradigm covers the questions of "what is knowledge (*ontology*), how we know it (*epistemology*), what values go into it (*axiology*), and the process of studying it (*methodology*)". Guba and Lincoln (1994) elaborate on the ontological, epistemological and methodological questions of a paradigm as follows.

The *ontological question* is "what is the form and nurture of reality and, therefore, what is there that can be known about it?" The *epistemological question* is "what is the nature of relationship between the knower, or would-be knower and what can be known?" The *methodological question* is "how can the inquirer (or would be inquirer) go about in finding out whatever he or she believes can be known?" (Guba & Lincoln, 1994, p. 108).

Four research paradigms are prevalent in social sciences: positivism/postpositivism, interpretivism, critical theory, and pragmatism—the latter being an emerging paradigm (Creswell, 2014; Easterby-Smith, Thorpe, & Jackson, 2012; Lincoln & Guba, 2000). The three paradigms most relevant to operations management research are as follows.

4.2.1. The Positivistic and Postpositivistic Paradigms

The positivistic ontology holds that the reality is positive and affirmative (this is also known as naïve realism) and therefore, it is ‘out there’ to be observed (Creswell, 2014; Crook & Garratt, 2011; Easterby-Smith et al., 2012; Guba & Lincoln, 1994). Furthermore, positivism assumes that reality is governed by “natural laws and mechanisms” and that these can be understood through cause-effect propositions, through precise measurements and control (Guba & Lincoln, 1994).¹⁷ The positivistic epistemology holds that the observer is independent (separable) from the object being observed and that the observer would study the phenomenon being observed without influencing the object being studied (i.e. work in a value free manner) (Creswell, 2014; Easterby-Smith et al., 2012; Guba & Lincoln, 1994). This property in the positivistic epistemology is known as dualism. Given the positivistic ontology, the positivistic methodology is propositional based—that is being driven by formulation and testing of hypotheses (Creswell, 2014; Easterby-Smith et al., 2012; Guba & Lincoln, 1994). The scientific method (not always the case in softer sciences such as biology and social science) is anchored on the positivistic paradigm (Easterby-Smith et al., 2012).

The *postpositivistic paradigm*, as the name suggests, emerged from positivism by softening the so called hard assumptions on the ontology and epistemology which governed science for many years (Creswell, 2014; Guba & Lincoln, 1994). Postpositivists assume that reality exists ‘out there’ but it can only be comprehended imperfectly, due to limitations in the “human intellectual mechanisms and the fundamentally intractable nature of phenomena” (Guba & Lincoln, 1994, p. 110). Associated with this notion is that the same reality can be comprehended in somewhat different ways based on the different approaches used by the researcher (Denzin, 1970; Wang & Duffy, 2009). Postpositivists therefore attempt to make knowledge claims using multiple sources of evidence (an approach known as triangulation) such as

¹⁷ Control means taking action to prevent extraneous factors confounding the results. These controls apply to both experimental methods as well as non-experimental methods (e.g. correlational methods such as surveys and Structural Equation Modeling covered in this chapter) used in positivistic research.

different data sources, different theoretical perspectives, and different methods so that they could understand the reality as objectively as possible (Creswell, 2014).¹⁸

Four quality criteria are frequently being used to assess the rigour of positivist and postpositivist research studies: reliability, validity, replicability, and generalisability (Creswell, 2014; Somekh et al., 2011; Wahyuni, 2012). Reliability refers to the consistency of the measures used to operationalise the constructs (Cronbach, 1951; Nunnally & Bernstein, 1994; Wahyuni, 2012) while validity refers to extent to which a construct measures what it is supposed to measure (Nunnally & Bernstein, 1994). Replicability and generalisability are criteria that stem from reliability and validity (Nunnally & Bernstein, 1994; Wahyuni, 2012). Replicability refers to the ability of a study being replicated (to achieve similar outcomes) while generalisability, which is also often known as external validity, refers to extent to which the findings being generalisable across the wider population (Crook & Garratt, 2011; Wahyuni, 2012).

4.2.2. The Interpretive Paradigm

The interpretive paradigm, also known as the constructivist paradigm holds belief systems that are polar-opposite to the positivistic/postpositivistic paradigms (Creswell, 2014; Guba & Lincoln, 1994). The stance taken by interpretivists is that knowledge is socially and experientially constructed through “intangible mental constructions” (ontology) and therefore the researcher and the object being investigated are inseparable in that the findings emerge as the observer interacts with the object of investigation (epistemology). For this reason, rather than using numerically coded data to test cause-effect hypotheses, interpretivists extensively make use of qualitative data through observation and in-depth interviewing of participants (subjects), involving single or multiple case studies (Creswell, 2014; Easterby-Smith et al., 2012). Yin (2011) maintains that the case study approach is the best approach to collect rich qualitative data to answer “how” and “why” type research questions as answering these questions require in-depth understanding of the context being studied.

¹⁸ Providing multiple sources of evidence (triangulation) is an important element in the interpretive and pragmatic research paradigms also (Creswell, 2004).

Lincoln and Guba (2000) prescribe four quality criteria (they collectively called them “trustworthiness” of a qualitative research study) to assess rigour of an interpretive (qualitative) study: credibility, transferability, dependability, and conformability. *Credibility* refers to imparting confidence in the reader on the truthfulness of the findings (e.g. prolonged engagement with the subjects, persistent observation, and triangulation); *transferability* refers to demonstrating that the findings could be applied in contexts other than what was observed (analogous to generalisability in positivism/postpositivism); *dependability* refers to demonstrating that findings are consistent (analogous to reliability in positivism/postpositivism); finally, *conformability* refers to demonstrating that the findings were not influenced by the researcher biases but the subjects’ responses (Lincoln & Guba, 2000; Yin, 2011).

4.2.3. The Pragmatic Paradigm

The emerging paradigm “pragmatism” focuses less attention on the ontological and epistemological positions; instead, a pragmatist focuses attention to the social research problem under investigation to choose methods that work best in answering the research question/s (Creswell, 2014; Johnson & Onwuegbuzie, 2004; Patton, 1990; Wahyuni, 2012). Creswell asserts that pragmatists believe that they ought to “stop asking questions about reality and laws of nature” and instead use both quantitative and qualitative data (i.e. use mixed methods) to provide a better understanding of the problem to be solved.

4.2.4. Researcher’s Paradigm

The nature of the researcher’s four research questions is such that these questions fit into a postpositivistic paradigm. The first research question concerns hypothesising relationships between *constructs*; the constructs would then be operationally defined for the purpose of measurement. In social and behavioural sciences the term “construct” is used to refer to a variable that is latent (directly unobservable) in nature (Peng, 2004). Any attempt to hypothesise relationships between constructs for the purpose of validating them is a positivistic/postpositivistic endeavour.

The second research question is about (statistically) observing the strengths of the hypothesised relationships between the constructs (the level of acceptance of Taguchi’s

Quality Philosophy is measured numerically through statistical modelling), which is practicing the hypothetico-deductive approach espoused in positivism.

The third research question looks at discovering the statistical and operational merits and demerits of Taguchi methods relative to the alternative robust design method (baseline), namely the response surface approach. The researcher makes this investigation in a propositional format (the proposition is that Taguchi methods fit to a Lean apparel manufacturing context better than the alternative method does). In testing this proposition, the researcher conducted robust design experiments in one of the factories to understand to what extent these experiments actually help the manufacturing organisation in producing a product that is robust against the noise created by the uncontrollable factors (the details in the next chapter). Conducting experiments is a positivistic/postpositivistic endeavour. Although the researcher had to engage with the staff in the factory to identify operational merits and demerits, the nature of these engagements/interactions (details in the next chapter) were similar to the engagement/interaction an engineer would have had in testing a product that they produced in the field. Thus answering the third research question does not require crossing the postpositivistic paradigm.

The fourth research question is about identifying the compelling forces and restraining forces (within the force field framework advanced by Lewin, 1951), when Taguchi methods are introduced in the Lean apparel manufacturing context being examined. Answering this research question required a greater level of engagement/interaction (details in the next chapter) with the staff in the factory than what was required in answering the third research question. This is because there were no experimental data at hand to make any value free judgement. Although secondary data were also used, most of the data used in answering the fourth research question were qualitative data that came from ethnographic engagements (details in the next chapter). In the next chapter, in introducing the case study (section 5.2), the researcher argues that the purpose of her case study is exploration and that she viewed the happenings through a postpositivistic lens, triangulating multiple sources of evidence (different data sources, different methods, and different theoretical positions) as espoused in the postpositivistic paradigm. Some may view that the researcher has adopted the pragmatic paradigm.

4.3. THEORETICAL MODEL BUILDING

4.3.1. The Hypotheses

The theoretical model (Figure 4.1) was developed to propose how Taguchi's Quality Philosophy relates to a Lean Manufacturing System. This conceptualised model, as mentioned earlier, consists with four constructs: the Lean Manufacturing System, Taguchi's Quality Philosophy, Continuous Improvement (CI), and Manufacturing Process Outcomes. In the model, the Lean Manufacturing System and Taguchi's Quality Philosophy are the two causal constructs; Manufacturing Process Outcomes is the effect construct; CI is a construct that mediates the causal relationships. There are six hypothesised relationships in the model. Formulation of each hypothesis is discussed in turn in the following paragraphs.

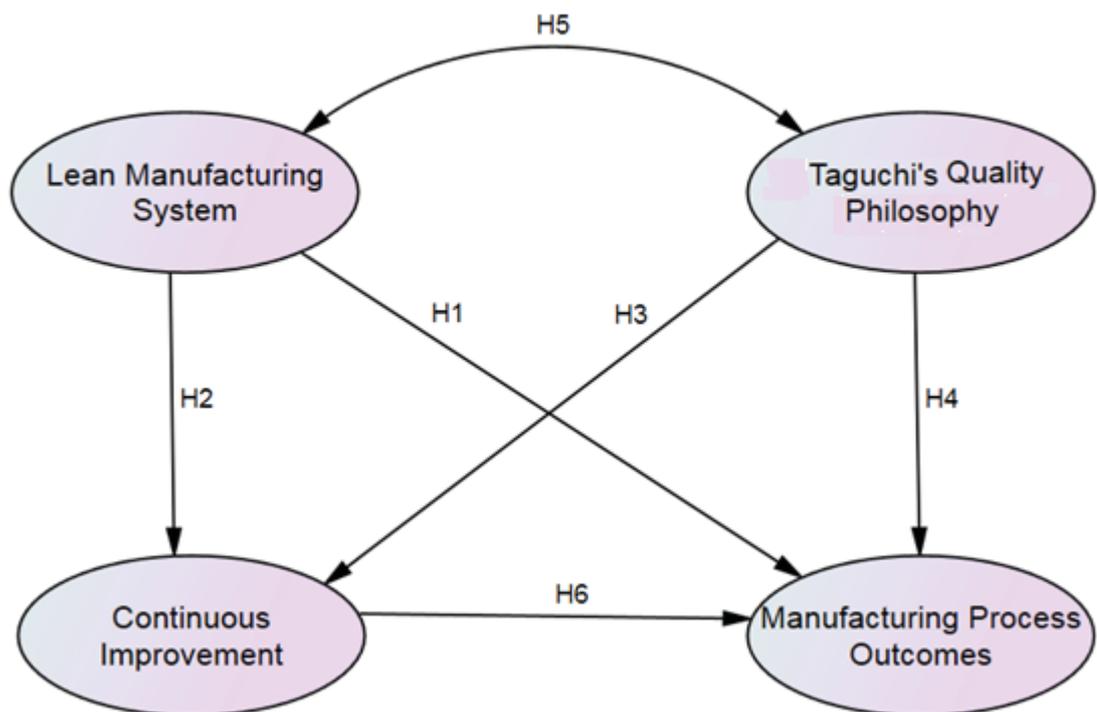


Figure 4.1: The proposed structural model

In Chapter 2 (section 2.2), using the literature, the researcher defined what is meant by a “Lean Manufacturing System”. To recap, a Lean Manufacturing System is the socio-technical system of the organisation that is engaged in creating value to the customers by eliminating waste and non-value adding activities from all activities of the value chain (Jayamaha et al., 2014; Liker, 2004; Shah & Ward, 2007; Womack & Jones,

2003). The organisational development term “socio-technical system” is used by the researcher to mean that the work (e.g. CI activities) that takes place in an organisation is a result of a complex interaction of the technical system and the social system of the organisation (Cooper & Foster, 1971; Pasmore, 1988). CI can be viewed as the state of continuously effecting improvements to products and processes. CI could be operationalised through activities that are organised and done (within the socio technical system) to achieve CI. Therefore CI can be viewed as the primary output of the Lean Manufacturing System.

The Primary Causal Relationship

According to the literature (e.g. Karlsson & Åhlström, 1996; Motwani, 2003; Shah & Ward, 2003; Stone, 2012; White, Pearson, & Wilson, 1999), the ultimate goal of a Lean Manufacturing System is to create *competitive advantage* by achieving Manufacturing Process Outcomes. These include increasing productivity, enhancing quality, shortening lead times, and reducing cost (Karlsson & Åhlström, 1996; Motwani, 2003; Shah & Ward, 2003; Stone, 2012; White et al., 1999). All of these outcomes do result in creating customer value. This leads to the first research hypothesis:

H1: A Lean Manufacturing System has a direct positive effect on Manufacturing Process Outcomes.

The Mediating Role Being Played by Continuous Improvement

The next step is to search for any mediating variable/s that affects (mediates) the relationship between Lean Manufacturing System (cause) and Manufacturing Process Outcomes (effect). The reader may refer to Wu and Zumbo (2008) for details on mediation and moderation in social research. Radnor et al. (2006) found that CI is an integral part of the culture of a Lean organisation to sustain the outcomes. Filho and Uzsoy (2011) found CI to be a salient feature in Lean (and also in Six Sigma) organisations.

Based on the five Lean principals defined by Womack and Jones (2003), identifying the value stream is a key step (the second step) in Lean. A value stream analysis always shows three types of activities: value-added activities, non-value-added activities that

can be eliminated immediately, and non-value-added but needed activities which are unavoidable with the current technology (Womack & Jones, 2003). Womack and Jones assert that non-value-added activities (those that can be eliminated based on current technology) need to be avoided continuously through small step improvement (kaizen). They also contend that big step improvements (innovation) will be required ultimately for reducing non-value-added but needed activities and for the survival of the organisation, in a competitive manufacturing environment.

Based on above literature, two types of relationships can be identified between the cause Lean Manufacturing System and effect Manufacturing Process Outcomes: (a) the direct effect Lean Manufacturing System \rightarrow Manufacturing Process Outcomes due to innovative improvements (kaikaku) and (b) the indirect effect due to the mediating role being played by CI (kaizen). This necessitates the following additional hypothesis:

H2: A Lean Manufacturing System has a direct positive effect on Continuous Improvement.

The Second Causal Variable Taguchi's Quality Philosophy

Before positing the remaining relationships of the causal model, it is important to explain what the researcher means by the term "Taguchi's Quality Philosophy" (see section 3.4.2.1 for more detail). By "Taguchi's Quality Philosophy" the researcher means Taguchi's assertion that products (and processes) need to be designed so as to show minimum variation around the target value (T) of the product's functional characteristic, given the uncontrollable factors that exist in production or in consumption—the rationale being the (quadratic) loss to society due to deviation of the product's functional characteristic (quality characteristic) from the target.

Based on Taguchi's Quality Philosophy, loss due to poor quality can be simply represented using quadratic loss function, $L = k(y - T)^2$ (in this formula, L is loss, k is the loss parameter or proportionality constant, y and T are the measured value and target value of the specific quality characteristic of the product respectively). Therefore through a replicated experimental design (based on Taguchi methods), aimed at minimising variation around the target value T (each replicate representing a specific

noise factor combination), the experimenter seeks to determine the control factor settings that minimise the Mean Square Difference (MSD).

Box, Bisgaard, and Fung (1988) showed that Taguchi's emphasis on minimising the MSD is in line with CI. This position has been endorsed in many subsequent articles (e.g. Antony, Hughes, & Kaye, 1999; Montgomery, 2009; Rowlands et al., 2000). Further, Locke and Jain (1995) have shown the importance of learning from direct experience through scientific designed experimental procedures such as factorial designs, response surface methods, Taguchi methods, evolutionary operations (EVOP) to bolster CI programmes.

Taguchi's robust parameter design approach mainly focuses on reducing variation of a product or process (Nair et al., 1992). More importantly, Taguchi's Quality Philosophy is the backbone of any robust parameter design approach (be it based on Taguchi methods or the alternative response surface approach to robust parameter design). Although Taguchi's robust parameter design approach is based on the experimental planning and data analytic procedures prescribed by Taguchi (collectively called Taguchi methods as explained in section 3.4.2) and the alternative robust parameter design approaches such as the response surface approach are based on the conventional experimental planning and data analytic procedures, both approaches aim to design a product (or process) whose functional characteristics are robust against the variability of uncontrollable factors that exist in the environment (Khuri & Mukhopadhyay, 2010; Montgomery, 2013). Minimising variation is at the very heart of CI (Bañuelas & Antony, 2003; Liker & Morgan, 2006). Taguchi's Quality Philosophy serves as the foundation on which all types of robust parameter design methods (e.g. Taguchi methods, response surface approach to robust parameter design) are developed. The third research hypothesis therefore is:

H3: Taguchi's Quality Philosophy has a direct positive effect on Continuous Improvement.

Box, Bisgaard, and Fung (1988) as well as the American Society for Quality (ASQ, 1996) assert that variability is the biggest bane in mass production. The above sources highlight that any reduction of variability will result in reduced scrap/rework and costs. Taguchi's Quality Philosophy focuses on variability and its overall impact to the

society. In addition, many years ago Philip Crosby, a well-known quality guru, claimed that it is always cheaper to do things right the first time (Crosby, 1979). Interpreting Crosby's assertion in conjunction with Taguchi's Quality Philosophy, it can be stated that quality has to be "designed in" (i.e. quality by design) to achieve high system quality levels (Gunter, 1987). This explains why Taguchi's robust parameter design approach (and hence by default the alternative approaches) focus on offline quality control as a part of product design and development (Roy, 2010).

The objective of a robust parameter design (based on Taguchi methods or alternative methods such as the response surface approach to robust parameter design) is to develop high quality products whose quality performance is less sensitive to uncontrollable factors, and thereby reduce loss to society, which results in Manufacturing Process Outcomes such as cost reduction, waste reduction, and efficiency improvement (Chen, Li, & Cox, 2009; Roy, 2010; Taguchi et al., 2005). Using systems thinking, it can also be argued that designing high quality products (system output) have a salutary effect on the customer and the external environment (Haines, 2000).

There are number of firms and industries that have not reaped real benefits through Taguchi methods (or alternative robust parameter design methods) mainly due to two reasons. Firstly, these firms/industries treat experiments in isolation. They do not integrate the experiments into the CI strategy (Rowlands et al., 2000). Secondly, Taguchi methods (or alternative robust design methods) aim to minimise variation in product and process performance by setting the process parameters right at the very outset, which is usually not the way most manufacturers achieve optimisation: *trial and error* (Mileham, Culley, Owen, & McIntosh, 1999; Razfar, Zinati, & Haghshenas, 2010; Yusoff, Mohamed, Hamid, Harun, & Ramly, 2004).

Taguchi methods (or alternative robust design methods) have demonstrated applications in various manufacturing industries such as plastic, automotive, electronic etc. (Kumar, Motwani, & Otero, 1996) to optimise scrap and rework rate, to increase process yield, to increase product performance such as mechanical strength, durability, and taste. For the aforementioned reasons Taguchi's Quality Philosophy is hypothesised to have a direct effect on Manufacturing Process Outcomes. Thus the fourth hypothesis is:

H4: Taguchi's Quality Philosophy has a direct positive effect on Manufacturing Process Outcomes.

Womack and Jones (2005b) crystallised a new paradigm in Lean taking into account the frustration and disappointment a customer suffers when using (consuming) a product: low reliability, durability, and poor performance (see section 2.2.2 for details). In articulating loss to society due to variation, Taguchi too was thinking about losses to the customer (as well as losses to the producer). Taguchi's Quality Philosophy measures quality losses as system-wide costs using the MSD. Further Taguchi and Clausing (1990) advised manufacturers to design products that do not fail in the field (their argument was that the factors that cause the variability of the functional characteristic of a product may exist out there in the field but not inside the factory) as this also does "simultaneously reduce defectives in the factory". Nicholas (1998) stated that manufacturing a product (or designing a process) to stay at its standard or target value results in zero variability, which equates to zero defects, and therefore, avoidance of waste resulting from poor quality such as product recalls (unsatisfactory or defective product functionality), rework, and scrap (as mentioned elsewhere, process waste can manifest in several forms, which need to be eliminated through continuous improvement). Therefore it is logical to hypothesise some degree of positive correlation between Taguchi's Quality Philosophy (i.e. the philosophical element of 'loss to society', which underpins Taguchi methods) and the Lean Manufacturing System. This gives rise to the fifth hypothesis:

H5: Taguchi's Quality Philosophy is positively correlated with the Lean Manufacturing System

What the above hypothesis implies is that, Taguchi's Quality Philosophy and the Lean Manufacturing System has some (positive) association, as seen by the practitioners of Lean philosophy.

In recent years, several types of organisations/industries have employed CI approaches as a management paradigm (Bessant et al., 2001; Caffyn, 1999; Singh & Singh, 2012). CI is playing an integral part of an organisation to sustain the outcomes achieved from Lean in the longer term (Walley, Stephens, & Bucci, 2006). As mentioned earlier, CI can be posited to be a mediator in between Lean and process outcomes. In addition,

application of Taguchi methods for robust design experiments in Lean Six Sigma style CI projects (e.g. Chen et al., 2010; Sahoo et al., 2008b; Thomas et al., 2008) also means that CI can be posited to be a mediator in between Taguchi's Quality Philosophy and Manufacturing Process Outcomes. To complete the aforesaid mediating relationships there is overwhelming support in the literature (Bhuiyan & Baghel, 2005; Bond, 1999; Caffyn, 1999; Singh & Singh, 2012) to suggest that CI has a positive effect on process outcomes. This gives rise to the final (sixth) hypothesis:

H6: Continuous Improvement has a direct positive effect on Manufacturing Process Outcomes

Basically, the theoretical model attempts to explain (on the whole) the attractiveness of Taguchi's Quality Philosophy to a Lean practitioner, as a proposition for improving the outcomes through superior product design (the direct effect on Manufacturing Process Outcomes) and continuous improvement of products and processes (the indirect effect on Manufacturing Process Outcomes).

4.3.2. Boundary Conditions and Other Features of the Theory Developed

The theory developed by the researcher (i.e. the set of six hypotheses mentioned in the previous section) is purported to be applicable within a boundary (delimitation) of manufacturing organisations that have gained sufficient maturity in Lean. Many organisations claim to be Lean organisations when they adopt few basic tools such as the 5S (Radnor et al., 2006). Such organisations are not regarded as mature Lean manufacturing organisations because Lean, as a sociotechnical system is much more than a few tools (Paez, Dewees, Genaidy, Tuncel, Karwowski, & Zurada, 2004; Shah & Ward, 2007). The researcher admits that the model has been tested using data collected from factories that produce apparels, which may limit the generalisability (hence the external validity) of the theory.

The theory has the following good features:

- The theory is parsimonious as it does not contain constructs that supposedly explain very little of the phenomenon of interest (Dubin, 1978; Whetten, 1989).

- The theory includes a mediating variable (CI) showing how the causal variables (Lean Manufacturing System and Taguchi's Quality Philosophy) affect the effect variable (Manufacturing Process Outcomes) through the mediating variable (Whetten, 1989).
- The theory has substantial relevance to practice (Corley & Gioia, 2011; Dubin, 1978).
- The boundary conditions of the theory are clearly specified (Forza, 2002; Whetten, 1989).
- The operational definitions (delimitations) of the theoretical constructs (section 4.4) are provided (Forza, 2002).

In addition to above, the parsimonious model developed by the researcher allows future researchers to augment the model to study moderating effects such as understanding how the organisational culture (or any other potential moderator such as type of technology) affects the hypothesised relationships.

4.4. DEVELOPMENT OF THE SURVEY QUESTIONNAIRE

Having developed the set of hypotheses that constitute the theoretical model (Figure 4.1), the next step was to provide operational definitions (i.e. devising measurement scales) for the four constructs of the theoretical model. The survey instrument (questionnaire) was developed exactly for this purpose. The 4-page survey instrument (Appendix A) consists of two parts. Part A of the questionnaire covers the demographic information about the respondent. Part B covers 40 statements related to the production environment of the respondent's manufacturing facility (therefore the operational definitions of the constructs are in Part B). In part B of the questionnaire, a 7-point Likert scale is used to seek agreement or disagreement to 40 statements on several facets related to the four constructs of the theoretical model (Figure 4.1). In the Likert scale that was used, code 1 indicates "Strongly Disagree" while code 7 indicates "Strongly Agree". Codes 2, 3, 4, 5 and 6 refers to "Disagree", "Somewhat Disagree", "Neither Disagree nor Agree", "Somewhat Agree", and "Agree" respectively. A seven point Likert scale is used to improve the reliability of the measurement scale (Nunnally

& Bernstein, 1994). For statistical analysis the Likert scale is considered as an “interval” scale (Flynn, Sakakibara, Schroeder, Bates, & Flynn, 1990). All survey items were *completely randomised* (the reader will note this from the random questionnaire item numbers under each construct) to minimise method bias (Conway & Lance, 2010; Zikmund, Babin, Carr, & Griffin, 2013).

In administering the survey, the anonymity of the respondents was maintained at all times and the survey (as well as the fieldwork covered in the next chapter) was conducted in accordance with Massey University’s human ethics guidelines (Appendix C). The survey instrument was developed by the researcher in English. The Researcher then translated the questionnaire to Sinhala (the mother language of the respondents) and requested an independent Sinhalese academic to back translate the Sinhalese version into English. This step was taken to ensure that there are no significant discrepancies between the original version and the translated version of the survey instrument (Brislin, 1970). The cover page of the questionnaires were personally signed by the researcher (in blue ink) and the questionnaire was designed to look as professional as possible to increase the response rate (Fowler Jr., 2014).

4.4.1. Operationalising Lean Manufacturing System

Fourteen (14) questionnaire items were designed to capture the conceptual domain of a ‘Lean Manufacturing System’. These 14 items were grouped into five (05) sub-domains in order to cover the philosophical and practical perspectives of Lean. Four of the five sub-domains represent the four Ps of a Lean organisation, as articulated by Liker: *philosophy* (long-term thinking), *processes*, *people and partners*, and *problems* (relentless application of root-cause analysis to solve problems) (Liker, 2004). The fifth sub-domain “visual factory” was added to represent a more complete representation of a Lean Manufacturing System (Antony, 2011; Hodge et al., 2011).

Philosophy (the 1st P)

Toyota has become the world’s largest car manufacturer because of its philosophy of aligning the whole organisation towards a common purpose and its long-term perspective of CI (Liker, 2004; Womack & Jones, 2003). These are the major principles of the “Toyota Way”, which Lean thinking is built upon (Liker, 2004). The

questionnaire item 32 captures whether or not company processes are aligned with the organisation strategy. The critical starting point of Lean thinking is to create value to the customer, which can only be defined by the customer (Womack & Jones, 2003). Questionnaire item 14 captures this philosophical view of Lean: customer is the ultimate arbiter of value (Forza, 1996). Lean organisations have a culture of developing exceptional individuals and teams who become thorough in all aspects of work including coaching others to perform (Hines et al., 2008; Liker, 2004). Questionnaire item 34 captures this characteristic of a Lean organisation.

Processes (the 2nd P)

The questionnaire items under ‘processes’ capture the organisational process that are put in place to eliminate internal waste and non-value adding activities. Elimination of non-value adding activities lowers the cost of product, which is the primary way customer value is created through Lean (Hines et al., 2004). Questionnaire item 23 captures JIT production, the primary goal of which is to continuously reduce and ultimately eliminate all types of waste (Camacho-Miñano, Moyano-Fuentes, & Sacristán-Díaz, 2012; Liker, 2004; Shah & Ward, 2007; Sugimori, Kusunoki, Cho, & Uchikawa, 1977). JIT production (pull production), which can be contrasted to push production found in traditional manufacturing, is based on the notion that the customer should pull the product (Womack & Jones, 2003). In traditional manufacturing (push production) goods are produced in advance according to a production plan and the stock produced is used to meet the customer demand (Bowen & Youngdahl, 1998; Holweg, 2007; Vokurka & Lummus, 2000). Question number thirty (30) captures the effectiveness of plant and equipment through planned maintenance (Camacho-Miñano et al., 2012; Demeter & Matyusz, 2011; Liker, 2004; Rivera & Chen, 2007). Poor plant and equipment maintenance is a primary cause of product nonconformities/defects (Schonberger, 2007), which affects the smooth flow of products or process.

People and Partners (the 3rd P)

It is argued that an organisation has to have the right culture to enjoy the full benefits of Lean (Bhasin & Burcher, 2006; Forza, 1996; Liker & Morgan, 2006). Understanding the people as well as their behavioural relationships is important for Lean to be effective

an organisation (Forza, 1996). Questionnaire item 39 captures the availability of multi skilled workers, who are required to maintaining a smooth flow. In keeping with Lean principles, questionnaire item 33 captures the opportunities provided by the organisation for its employers to overcome challenges the employees face in effecting CI successfully (Forza, 1996; Liker & Morgan, 2006).

Supplier relationship for mutual benefit is a major feature in a cooperate culture reflecting a Lean organisation (Anderson et al., 1994; Bhasin & Burcher, 2006; Forza, 1996; Levy, 1997). Hence questionnaire item 18 captures company relationships with the suppliers. A Lean organisation not only values “respect for people” but also values the growth and development of its human resources, which is achieved by providing opportunities and facilities for growth (Anderson et al., 1994; Bhasin & Burcher, 2006; Jayamaha et al., 2014). Questionnaire item 40 captures the potential for growth and development of the human resources.

Problems (the 4th P)

Two items of the construct ‘Lean Manufacturing System’ relate to ‘problem solving’ (King & Lenox, 2001; Liker, 2004; Liker & Morgan, 2006). Day to day experience the employees gain by confronting with the challenges and problems on the job is a rich learning source when it becomes necessary to adapt to new situations (Daudelin, 1996). Questionnaire item 24 captures whether or not the organisation being assessed is a true learning organisation; learning is a key characteristic of effective problem solving. The other key characteristic of efficient and effective problem solving (the Lean way) is through standardisation of methods used to diagnose problems, which is captured by questionnaire item 31 (Liker, 2004; Liker & Morgan, 2006).

Visual Factory

The ‘visual factory’ is also an important facet in Lean (Bhasin & Burcher, 2006; Liker, 2004). A visual factory uses communication methods, in the form of visual information, to drive the operations and processes in real time (Parry & Turner, 2006). Majority of communication in a Lean organisation is accomplished using visual tools, which bring numerous benefits (e.g. increase productivity, reduce defects and mistakes, facilitates communication etc.) to the process (Parry & Turner, 2006). Questionnaire item 25 is

used to capture the ‘visual factory’. The questionnaire item 5 captures the use of 5S, a key facet of Lean which is used to make sure that the workplace is thoroughly organised visually. Questionnaire item 37 covers the use of Value Stream Mapping (VSM), a core visual tool (also a core principle) of Lean (Womack & Jones, 2003); VSM is used to understand, design or manage the process in order to increase customer value (Hines et al., 2008; Rother & Shook, 2003).

4.4.2. Operationalising Taguchi’s Quality Philosophy

Seven operational measures were developed to capture the conceptual domain of the construct ‘Taguchi’s Quality Philosophy’. While a philosophy in itself does not produce an outcome, in the case of the quality philosophy articulated by Taguchi, the philosophy acts as foundation (driver) on which Taguchi methods on quality are built upon.¹⁹ Stated alternatively, Taguchi’s Quality Philosophy is the reason for the existence of Taguchi methods in quality control and quality improvement (details in section 3.4.2).

Taguchi’s Quality Philosophy embeds two complementary propositions: poor quality is a loss to society, and high system quality can be achieved by designing-in quality at the design stage of a product/process (Gunter, 1987; Rowlands et al., 2000; Roy, 2010; Unal & Dean, 1991). The latter position is also known as quality in design (as opposed to quality of conformance) in the quality literature (Dale et al., 2013). Thus questionnaire items 19 and 20 have been developed to capture Taguchi’s assertion that “poor quality is loss to society”, particularly to the producer and end customer. Questionnaire item 29 addresses the doctrine “quality should be designed-in” (Ross, 1996; Roy, 2010; Taguchi & Clausing, 1990; Unal & Dean, 1991).

Taguchi’s view that loss to society increases quadratically as the functional characteristic moves away from the target value can be a revelation to those who rely on the traditional “goal post” approach to quality, where any measurement of the product’s functional characteristic between the specification limits is treated as being equally good, as far as the fitness for use of the product is concerned (Gunter, 1987; Ross, 1996;

¹⁹ In fact, alternative experimental designs proposed by the statisticians subsequently, still use Taguchi’s Quality Philosophy including the position that robust parameter design is a very efficient method of making products (or processes) robust against the variations in uncontrollable factors (Montgomery & Runger, 2010; Roy, 2010).

Roy, 2010; Taguchi & Clausing, 1990). Questionnaire item 13 thus addresses Taguchi's quality loss function proposition.

Taguchi's philosophical paradigm on quality is embedded in Taguchi methods which draws some of its roots from classical DoE methods. A salient feature in the classical DoE method is to change the multiple variables simultaneously to understand the complex system being studied (Gunter, 1987; Montgomery & Runger, 2010; Ross, 1996; Roy, 2010). This feature is preserved in the DoE methods prescribed by Taguchi. Questionnaire item 10 (reverse-coded) is designed to capture this very important feature of simultaneous manipulation of multiple factors in planned experimentation.

Taguchi methods have been mainly developed to produce robust products and processes that become insensitive to noise (changes in the levels of environmental factors), whose controllability is beyond the producer's hands (Ross, 1996; Rowlands et al., 2000; Roy, 2010; Taguchi & Clausing, 1990; Unal & Dean, 1991). Questionnaire items 27 (robust products) and 12 (robust production processes) address the importance of developing robust products and processes to reduce the overall loss to society, based on Taguchi's quality Philosophy.

It is important to note that the researcher is only attempting to operationalise Taguchi's Quality Philosophy and not the depth and breadth of the application of Taguchi methods as such. None of the Lean factories to which the questionnaire was dispatched to, use Taguchi methods. It is suspected that some questionnaire items (e.g. questionnaire item 10) may actually be attempting to measure. Taguchi's RPD approach (Taguchi methods); Taguchi's Quality Philosophy is only the foundation element of Taguchi's RPD approach (details in section 3.4.2); it is assumed that unidimensionality tests will weed out irrelevant survey items. The researcher's *central thesis* is that Taguchi's Quality Philosophy resides in Lean organisations and that with the right tools (Taguchi methods), they could bring this philosophy into fruition. This is the *raison d'être* of research objectives 2 and 3 (also research questions 3 and 4).

4.4.3. Operationalising Continuous Improvement

Eleven questionnaire items were developed to operationalise CI along the 5 themes identified by Kaye and Anderson (1999). These are *leadership*; *strategic focus*;

organisational culture and focusing on employees; processes, standardisation and measurement; and learning from results (the survey items for ‘learning from results’ were removed at the peer review stage; see footnote #20).

Leadership and Strategic Focus

CI is a perpetuating activity that is developed over time as a dynamic process embedded in the organisational culture (Besterfield, Besterfield-Michna, Besterfield, Besterfield-Sacre, Urdhwareshe, & Urdhwareshe, 2011; Camacho-Miñano et al., 2012; King & Lenox, 2001). Questionnaire item 22 captures the employers’ understanding on the organisation’s strategic goals and objectives that help managers to focus and prioritise improvement activities (Bhuiyan & Baghel, 2005; Caffyn, 1999; Kaye & Anderson, 1999). Leadership plays a key role in causing CI activities to become sustainable (Bessant et al., 2001). This aspect is addressed in questionnaire item 16.

Organisational Culture and Focusing on Employees

A favourable organisational culture is also considered to be a necessary condition for making CI activities sustainable (Kaye & Anderson, 1999). Bessant et al. (2001) assert that CI activities are not day to day activities specified in the work instructions or the standard operating procedures meant for the employees. They argue that CI activities are embedded in every aspect of work to the extent that CI becomes a key aspect of the organisational culture, which is captured in questionnaire item 4. It is well documented in the literature that managers who believe in Lean and Quality never blame people for their mistakes but encourage people to learn from the mistakes to understand what went wrong with the system (Bessant et al., 2001; Liker & Morgan, 2006). This is captured in questionnaire item 36. Questionnaire item 11 has been used to capture the important leadership initiative of rewarding the people appropriately by taking into account the nature of the quality/process improvement problem and the solution provided (Bessant et al., 2001); the more non routine the improvement problem the greater the incentive provided should be.

Processes, Standardisation and Measurement²⁰

Standardisation is the foundation for the CI activities (Berger, 1997). Imai (1986 p. 74), a key proponent of Kaizen, emphasised that “there can be no improvement where there are no standards”. Questionnaire item 3 captures the degree of task and work process standardisation. Questionnaire items 7 and 15 monitor the improvement of CI results. Questionnaire item 17 captures the use of appropriate tools and techniques to support the CI activities (Bessant et al., 2001; Bhuiyan & Baghel, 2005; Caffyn, 1999; Singh & Singh, 2012).

Physical layout of the product flow is captured in questionnaire item 8 (Bhasin & Burcher, 2006; Liker, 2004; Shah & Ward, 2003) and the efficiency of changeover time (for converting manufacturing process from running one type of product to another type of product or batch) is captured in questionnaire item 21 (Flynn et al., 1995; Jayaram et al., 2010; Rivera & Chen, 2007; Schonberger, 2007). Both the physical layout and quick changeover are salient features of a JIT system (Cua, McKone, & Schroeder, 2001) as well as continuously improving activities which reduce the changeover time and enhance the usage of space, while reducing unnecessary motions at the plant.

4.4.4. Operationalising Manufacturing Process Outcomes

As stated before, the ultimate goal of implementing Lean production in an operation is to increase productivity, enhance quality, shorten lead times, reduce cost—all of which result in creating customer value (Karlsson & Åhlström, 1996; Motwani, 2003; Shah & Ward, 2003; White et al., 1999). Apart from the above goals, consideration on ‘Lean consumption’ (Womack & Jones, 2005b), which takes into account what the customer experiences in consuming (Taguchi & Clausing, 1990) the product, is also considered to be a goal in contemporary Lean thinking. For several questionnaire items under Manufacturing Process Outcomes, a two-year time span was considered because the factories to which the questionnaire was administered (all factories belong to the same

²⁰ At the peer review stage (section 4.6.1) of the questionnaire was discovered that the sub-domain ‘processes, standardisation and measurement’ is an integral part of Lean and therefore there is a substantial overlap between the two constructs Lean Manufacturing System and CI (data also supported this). To prevent further overlap, the two questionnaire items that were initially designed to represent the sub-domain ‘learning from results’ was removed at the peer review stage; hence there are no questions to represent the subdomain ‘learning from results’ under CI.

organisation) appeared to have attained Lean maturity since 2009-2011 (the details are given later), since embracing Lean.²¹

The construct Manufacturing Process Outcomes is measured using 8 questionnaire items. These items represent both avenues of value creation: increasing the value through eliminating non-value adding activities/waste and by creating additional value by developing superior products/customer solutions (Hines et al., 2004). Questionnaire items 9 and 28 address the quality performance results of the organisation (Camacho-Miñano et al., 2012; Demeter & Matyusz, 2011; Jayaram et al., 2010; Karlsson & Åhlström, 1996; Pavnaskar, Gershenson, & Jambekar, 2003; Schonberger, 2007; Shah & Ward, 2003). Manufacturing lead time, which is a function of cycle time, is a primary measure of the presence or the absence of non-value adding activities/waste. Relatively shorter cycle times reflect greater production efficiency (less waste/non-value adding activities). Questionnaire items 6 and 35 capture improvements in the cycle time (Bhasin & Burcher, 2006; Camacho-Miñano et al., 2012; Demeter & Matyusz, 2011; Flynn et al., 1995; Jayaram et al., 2010; Karlsson & Åhlström, 1996; Pavnaskar et al., 2003; Schonberger, 2007; Shah & Ward, 2003) and product development time (Jayaram et al., 2010; Schulze & Störmer, 2012) respectively, over the last two years.

Cost reduction (Schulze & Störmer, 2012) and quality risk assessment (Camacho-Miñano et al., 2012; Karlsson & Åhlström, 1996; Shah & Ward, 2003) are also considered as Manufacturing Process Outcomes. This is because cost reduction reflects less waste/non-value adding activities while quality risk assessment reflects the probability of success of new products in the market place. Questionnaire items 26 and 38 capture cost reduction and quality risk assessment respectively. Questionnaire items 1 and 2 capture the effectiveness of innovations in both processes and products which are considered to be leading indicators of customer value creation (Hines et al., 2004).

²¹ The organisation implemented Lean in their 31 factories in stages, starting from 2005. The researcher assumed that it takes 5 years (minimum) to attain some level of Lean maturity. Based factory in which the researcher conducted the fieldwork, including conducting robust design experiments, was the first to go Lean in early 2005.

4.5. THE SAMPLING FRAME, RESPONDENTS AND DATA COLLECTION

In survey research, the sample selection process is as important as the data collection process (Fowler Jr., 2014). This is because the quality of sample data depends on the proportion of people from whom the data are actually collected.

Testing of the theoretical model was done using data collected from the respondents (front line workers and managers) in 31 factories belonging to the largest apparel manufacturing organisations in Sri Lanka. The organisation has an annual turnover of US\$ 1.0 billion approx., and it is a mature Lean organisation. The 31 factories of the Lean organisation belonged to the Western, Southern and Central provinces of Sri Lanka, where the official language is Sinhala. In the Sri Lankan culture top level and upper middle level managers use English as their working language, while the rest use the native language (Sinhala or Tamil, depending on the region). This is the reason why two versions of the questionnaire (English and Sinhala) were necessary. With peace returning to the country following a period of protracted civil war, the organisation is now expanding its operations to the Northern and Eastern regions of the country where the official language is Tamil. These new factories were not included in the study as it was assumed that they may not have gained the required level of maturity in Lean to respond reliably to the questionnaire.

Due to agreements reached between the researcher and the Lean organisation, the name of the Lean organisation cannot be disclosed. In the next chapter (section 5.2.2) the researcher has described the key Lean operations (supply chain activities are not covered) in relation to one of the factories belonging to the organisation. At the time of data collection (October 2013 through to mid-January 2014) all 31 factories have had exposure to Lean for at least five years.

The units of measurement, for the purpose of administering the questionnaire, were the blue collar workers and managers in all the factories excluding those who are not familiar with the Lean operations (e.g. staff managers such as the finance managers and support staff). To obtain a requisite number of responses for SEM modelling, a sample size of 40 potential respondents per factory, split evenly between blue collar workers and managers (ranging from work supervisors to top managers) was deemed adequate. This resulted in a disproportionate stratified sample (Cooper & Schindler, 2014);

approximately 80% of staff in each factory are blue collar workers. The reader may note that the strategy of obtaining a wide representation of managers has been adopted by other researchers also (e.g. Evans, 2004; Flynn & Saladin, 2001), in order to get a more balanced view on the statements made in a survey instrument. In the case the researcher's study, as mentioned earlier, the 40 Likert-type survey questionnaire items provide 40 statements related to the four constructs of the theoretical model (Figure 4.1).

There was diversity within each factory, since each factory has a cutting department, production/sewing department, quality control department, work study department that provide value addition to the garments being produced. Also there was diversity between different factories of the organisation. Different factories produce different garments and more importantly, they compete with each other to outperform in Lean key performance indicators (KPIs). This diversity was deemed necessary as there should be sufficient variability in the responses received.

1240 printed copies (40×31) of the questionnaire were dispatched (along with blank envelopes to enclose the duly completed questionnaires) in October/November 2013 to the 31 human resource (HR) managers in each manufacturing facility, using a local bulk mail system in Sri Lanka. Consequently, each HR manager received 40 copies of the questionnaire to be distributed in their manufacturing facility. The HR managers, who acted as coordinators of the project during the data collection phase, were asked to pick 40 potential respondents at random from their facility, maintaining a 50-50 balance between managers and front line workers. However, the HR managers were asked to distribute the questionnaires only among team leaders (the only group that represents blue collar workers) and staff above the rank of the 'team leader' who are engaged in 'line management roles'; this is to ensure that the survey would only be administered on respondents who are very familiar with the Lean operations in their respective factories. The HR managers were also asked to accept only sealed envelopes as responses. Further, they were asked to dispatch the completed questionnaires that they collected (as bulk mail) within 4 weeks from receipt to a Sri Lankan address. Responses were received at the Sri Lankan address within 5-8 weeks from dispatching the questionnaires (a gentle reminder was sent in the third week and a two-week extension of time had to be given to those who requested for an extension of time). The responses (duly completed questionnaires) were then relayed back to New Zealand

using a reputed international courier company (the number of responses received and other details are found in section 6.3).

4.6. TESTING THE QUESTIONNAIRE AND THE THEORETICAL MODEL

Prior to dispatching the questionnaires for data collection, the content of the questionnaire was reviewed in two stages.

4.6.1. Peer Review

For the purpose of *face validity*, the draft survey questionnaire was first content-reviewed by six academics (two of them were researcher's supervisors, two academics were from New Zealand, one academic was from Sri Lanka, and one academic was from Malaysia) who were knowledgeable about the contents in the questionnaire. In addition, the Sri Lankan academic and the Malaysian academic, as well as the researcher's primary supervisor were familiar with the context (apparel manufacturing factories in Asia) in which the questionnaire would be administered. Face validity is a subjective assessment of the completeness of the survey instrument, in terms of what it is supposed to measure. Face validity is a form of *content validity* (Cooper & Schindler, 2014; Forza, 2002). Upon content review (the English version), emendations were made to the questionnaire (few changes to wording and deletion of some survey items).

4.6.2. Pretesting and Pilot Testing

In survey research, it is a good practice to pilot test a survey instrument with a small sample to reduce the risk of the full scale study running into difficulties due to issues with the content of the survey instrument as well as the survey administration (De Vaus, 2002; Groves, Fowler, Couper, Lepkowski, Singer, & Tourangeau, 2009). More recently, in addition to pilot testing, administering the survey instrument before a small group (say 5 to 10) of representative respondents to physically observe how they answer the questions (e.g. to physically observe how they responded to survey items) has also become popular (Groves et al., 2009). Since the respondents of the researcher's study were based in Sri Lanka, due to timing issues (the researcher could not be present in Sri Lanka at the time of testing the survey instrument), pretesting was not considered.

The questionnaire (both Sinhala and English versions) was pilot tested in a subsample ($n = 20$) of the relevant population and the respondents were asked to comment on the clarity of the questionnaire (only two factories were chosen). The subsample used for pilot testing consisted of 10 managers and 10 frontline workers. Out of the 20 who responded, 14 responded to the Sinhala version and 6 responded to the English version. There were no comments from any of the 20 respondents on the clarity (or any other issue) of the questionnaire.

The six who responded in English were asked (after two weeks from receipt of the pilot responses) whether they would like to respond to the Sinhala version also, in order to test the translation accuracy. Tallying the Sinhala version responses with the English version responses showed that there were no notable differences in the responses, implying that both versions can be considered to effectively measure the same thing.

4.6.3. Verifying the Absence of Common Method Bias

Common method bias (also known as common method variance, method variance and method bias) is a potential issue in measurement instruments such as surveys, where the cause variables and effect variables are measured using the same instrument (Lance, Dawson, Birkelbach, & Hoffman, 2010; Podsakoff, MacKenzie, Lee, & Podsakoff, 2003; Podsakoff, MacKenzie, & Podsakoff, 2012). Common method bias refers to the biasing effect (hence systematic error) that may occur when two correlated constructs are measured using the same (common) method. Absence of substantial method bias was statistically verified using “Harman’s single factor test” (Podsakoff et al., 2003). The details of the test are in section 6.4.1. The principal components analysis required for conducting Harman’s single factor test as well as descriptive statistical analysis of the study was performed using IBM SPSS version 21 software package.

4.6.4. Establishing Construct Validity and Scale Reliability

Construct validity refers to the extent to which the constructs measure what they purport to measure (Cooper & Schindler, 2014; Nunnally & Bernstein, 1994). Construct validity is measured objectively using statistical techniques. As such, construct validity is an important form of measurement validity in positivistic research.

IBM AMOS version 21 *Structural Equation Modelling* (covariance based) software package was used to test construct validity and the hypothesised theoretical relationships in model. The covariance method of Structural Equation Modelling (details in section 6.2.1) is the preferred method of model testing over piecemeal methods such as the *partial least squares method* (details in section 6.2.2). The construct validity tests included confirmatory factor analysis for factorial validity and analysis of correlations between measures and the constructs for the purpose of *convergent validity* and *discriminant validity*.

Scale reliability is a necessary but not a sufficient condition for construct validity (Nunnally & Bernstein, 1994). Scale reliability refers to extent to which the measures of the scale appear to be internally consistent (i.e. inter-correlated) based on the test scores (Nunnally & Bernstein, 1994). Two scale reliability coefficients Cronbach's alpha (Cronbach, 1951) and composite reliability coefficient (Werts, Linn, & Jöreskog, 1974) as well as the Average Variance Extracted (Fornell & Larcker, 1981) were used as measures of reliability (see section 6.4.4 for details).

4.6.5. Model Testing

The model testing included two steps. In the first step, the researcher established that the assumed theoretical model (including the measures used to capture the constructs) is a good fit to data, in a covariance sense (Byrne, 2010; Kline, 2011; MacCallum & Browne, 1993). Many authors interpret this test to imply that the hypothesised theoretical model is tenable (MacCallum & Browne, 1993). In the second step, the researcher examined the model parameters and its statistical significance to determine whether or not the hypotheses are supported by the data.

4.6.6. The Assumptions

No piece of scientific work is complete unless the scientist makes their assumptions explicit. The following assumptions were made by the researcher for the methodology covered in this chapter.

- All 31 Lean factories gained sufficient degree of maturity from at least five years of implementing Lean. By “maturity” the researcher means sufficient

understanding on Lean to enable the respondents to understand the questionnaire unambiguously.

- The human resource (HR) managers (in each factory) to whom the questionnaires were dispatched for distribution have distributed the questionnaires in a random fashion, as advised to them by the researcher; that is, they would not “pick and choose” certain employees to fulfil their personal agendas (if any).
- Any difference between the English and Sinhala versions of the questionnaire would be practically negligible.²²
- The staff has responded to the questionnaire without any duress from the factory management to respond in a particular way.
- Although there is variability between factories on operational aspects (e.g. Lean maturity, size, type of product being produced), because all factories are owned by the same organisation, the organisational culture and other situational factors that could potentially moderate the hypothesised relationships remain inactive (see Shah and Ward, 2003). If this was not the case, the situational factors could have potentially moderated the hypothesised relationships (Figure 4.1). In other words, the researcher assumes that by choice (i.e. by holding the situational factors constant), there would not be significant moderation of the hypothesised relationships.

4.7. CHAPTER SUMMARY AND CONCLUSION

This chapter covered the methodology used to achieve the first research objective: to formulate and statistically test a theory that predicts and explains how *Taguchi's Quality Philosophy* and *Lean* management jointly contribute towards improving the operational performance in a mature Lean apparel manufacturing environment. In

²² The researcher found that translating some English sentences into Sinhala was challenging because some Sinhalese words in science and technology are rarely used in everyday communication. On one hand the researcher had to ensure that the meaning will not be lost in translation. On the other, researcher had to ensure that the Sinhala version is understood by everyday Sinhala user. Pilot testing was very useful in this regard.

achieving the said research objective, the researcher answers her first two research questions. The chapter began with a brief review of available key research paradigms to conduct the study and justification of the chosen paradigm: postpositivistic (section 4.2). In the next section (section 4.3) the researcher showed how she developed her theory (also represented as a model in Figure 4.1) using six interrelated hypotheses. In the same section (subsection 4.3.2) the researcher showed some good features of her theory. The researcher's central thesis is that Taguchi's Quality Philosophy resides in Lean organisations and that with the right tools (Taguchi methods), they could bring this philosophy into fruition. None of the factories from which data were collected to test the model used robust parameter design methods as part of product development or quality improvement (e.g. Six Sigma style quality improvement projects that use RPD methods).

In testing the researcher's theory the main objective the researcher attempts to achieve is to demonstrate that Taguchi's Quality Philosophy is acceptable to Lean practitioners in the apparel industry (see the second research question in section 3.6.2). Of course there is no point in having a philosophy or a good idea unless that philosophy or the idea can be put into practice. In fact, this is what the researcher attempts to examine through the methodology described in the next chapter. The next chapter (Chapter 5) therefore describes the methodology that was adopted to study what happens when Taguchi's Quality Philosophy is put into practice. More specifically, the next chapter describes the methodology that was adopted to answer the remaining research questions and thereby achieve the remaining research objectives.

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CHAPTER 5

FIELDWORK AT THE CASE STUDY PRODUCTION FACILITY

“The proof of the pudding is in the eating”

5.1. INTRODUCTION

This chapter covers the methodology that was used to answer the third and fourth research questions (section 3.6.2), which relates to understanding the technical and nontechnical issues (e.g. social, behavioural, cultural and human resource issues) that may arise in using robust parameter design approaches to solve variation problems in a Lean apparel manufacturing environment. As such, this chapter covers the second phase of the research project, which actually involved the application of Taguchi’s robust parameter design (RPD) approach (Taguchi methods), the response surface alternative, and other related fieldwork. More specifically, this chapter describes the fieldwork carried out at one of the 31 apparel manufacturing factories belonging to the Lean manufacturing organisation. Due to agreements reached between the researcher and the Lean organisation, neither the name of the Lean organisation nor the name of the factory in which the fieldwork was conducted is disclosed. The factory is based in Kandy, Sri Lanka. For ease of reference this factory will be referred to as the *case study factory*, or sometimes, the *factory*, from this point onwards.

A substantial portion of this chapter is allocated to describing the RPD experiments (mostly the main experiment that was conducted). The experiments were designed primarily to optimise the sewing parameters to minimise the variability of a critical quality characteristic (robustness of other quality characteristics were also examined) of a high end women’s garment produced in the case study factory (details follow). The experiments were just a means to an end and not the end in itself. One can only claim that Taguchi’s RPD approach complements Lean (or otherwise) if this approach has been tried out in a Lean environment, and hence the experiments. The experiments (and the associated fieldwork that prepared the staff in the factory to design the experiments) were foremost the focal point for engaging and interacting with the staff (ranging from frontline workers to senior managers) by the researcher to collect qualitative data. The

qualitative data, which were collected through personal observations (the most widely used mode), planned interviews, unplanned meetings, and document inspection, were as important as the quantitative data collected from the main experiment itself, to answer the third and fourth research questions, and thereby achieve the associated research objectives (objectives 2 and 3 mentioned in section 1.6.2). The rest of Chapter 5 is organised as follows.

Section 5.2 introduces both the methodology literature on the case study approach (section 5.2.1) as well as the case-study organisation and factory itself, through a brief description of its Lean operations system (section 5.2.2). Section 5.3 introduces the product that is faced with a substantial variation problem (robustness problem), a summary of all the field activities, along with the definition of the variation problem, and how the researcher and the quality improvement team went about in identifying the factors that need to be manipulated in the RPD experiment/s. Section 5.4 covers two areas: (a) the assessment of the precision of the measurement system that is used to measure the main response variable, and (b) the assessment of the stability and capability of the manufacturing process that produced the product faced with the variation problem. The latter (process capability assessment) provides the baseline values on process variability (e.g. population standard deviation) and capability prior to conducting the RPD experiment for quality improvement. Section 5.5 covers the details of the RPD experiment in proper. Section 5.6 covers the qualitative research methods and how researcher's fieldwork falls in line with the norms of ethnography.

All of the sections mentioned above cover the methodology that was used to answer the third research question (RQ3): *What are the statistical and operational merits and demerits (if any) of using Taguchi methods over conventional robust design experimental methods in solving important quality problems in apparel manufacturing?*

Section 5.7 covers the methodology that was used to answer the fourth research question (RQ4): *What drivers and what restraints do apply when Taguchi methods are actually being introduced in a mature Lean environment in the apparel industry?* More specifically, section 5.7 covers the theoretical framework to which the fourth research question relates to and the data collection methods used by the researcher to answer the two research questions related to this chapter: RQ3 and RQ4. Finally, section 5.8 provides a summary of the chapter.

5.2. THE CASE STUDY

Research questions 3 and 4 have been answered by the researcher using the case study methodology, within a post-positivist paradigm. Prior to introducing the case-study factory itself, the researcher examines the relevant methodological literature on case study methodology as follows.

5.2.1. Case Study Methodology

In social sciences (particularly in management and related disciplines) case studies are used to serve two different purposes: to teach the practical application of theory to the students (such case studies are known as teaching cases), and to understand a social phenomenon under a real world setting. This section is not about teaching cases but about cases used to understand real world happenings. Due to the flexibility of the case study approach, case studies can be used to understand wide ranging social phenomena (Myers, 2013; Thomas, 2011; Yin, 2014). Yin defines a case study as follows.

Case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident

(Yin, 2014, p. 16)

Thomas (2011) observes that while it is important for a social science case study to be classified based on its purpose and the approach (theory seeking, theory testing, or exploration) as this legitimises the process that has been adopted (a single case design or a multiple case design), the most fundamental classification elements of a case study are the subject (the case itself, without which there is no case study) and the object (the analytical frame in which the object is viewed) of the study. Barratt, Choi, and Li (2011) assert that the most fundamental requirement of a study that uses the case study methodology is to justify of the case study approach itself (as opposed to the alternative survey-based research).

Social science scholars subscribing to both positivist (e.g. Beverland & Lindgreen, 2010; Shanks, 2002; Yin, 2014) and intepretivist (Andrade, 2009; Barratt et al., 2011; Myers, 2013; Voss, Tsikriktsis, & Frohlich, 2002) paradigms observe that case studies

can be undertaken within positivist or an interpretivist paradigm adopting an inductive approach or a deductive approach, involving a single case design or a multiple case design, using qualitative and/or quantitative data. Darke, Shanks, and Broadbent (1998) contend that while validity (construct validity and internal validity), reliability and generalisability (external validity) are the criteria for rigour in positivist case study research, “statistical generalisation to a population is not the goal of case study research”, because cases are not sampling units. However, they contend that a well-designed case study can claim “analytical generalisability” through the plausibility of the logical reasoning provided by the researcher in describing the results.

5.2.1.1. Justification of the Case Study Approach

In responding to the call made by Barratt et al. (2011), the researcher has resorted to the case study methodology to answer the third and fourth research questions, because her objective is *exploration* (rather than theory generating or theory testing) using a post-positivist lens. There are too many gaps in the literature to test a complete theory on the integration of Taguchi’s RPD approach in a Lean environment. Therefore, the researcher attempted to bridge this gap in two phases. In the first phase of the overall study (the methodology was covered in Chapter 4), through the first and second research questions, the researcher examines the conceptual compatibility between Lean and Taguchi’s RPD approach (more technically precisely, Taguchi’s Quality Philosophy) in theory testing mode, using the survey research methodology. In the second phase of the overall study to which this chapter relates to, the researcher explores the compatibility of between Lean and Taguchi’s RPD approach from a practical standpoint, using somewhat complimentary research questions (i.e. RQ3 and RQ4), in trying to understand what happens in the Lean environment when Taguchi’s RPD approach is put into practice. This type of an exploration is only possible through a case study design.

5.2.1.2. Typology

The researcher classifies her case study using the typology prescribed by Thomas (2011), as follows. The *subject* (unit of analysis) of the case study is a key Lean organisation (as opposed to a locally known organisation or an outlier organisation),

represented by one of its manufacturing facilities. The *object* (the analytical frame in which the object is viewed) is adaptation of a supposedly complementary technique (Taguchi’s RPD approach) within a Lean environment. The *purpose* of the study, as mentioned earlier, is exploration. Therefore, the *process* that she uses is a single, retrospective case study design, which enables her to increase the depth of her exploration. Whilst a multiple case study design would have provided greater analytical generalisability, that would have come at the expense of having to utilise more resources (e.g. multiple researchers deployed in multiple sites), which is not possible in a doctoral study. The advantages and disadvantages of a single case design over a multiple case design, based on the descriptions provided by Voss et al. (2002), are shown in Table 5.1 below.

Table 5.1: A Single Case Design vs Multiple Case Design (Summarised from the Descriptions Provided by Voss et al., 2002)

<i>Single Case Design</i>	<i>Multiple Case Design</i>
<i>Advantages</i>	
Opportunity for making in-depth observations and analysis	Helps to guard against observer bias
Suits longitudinal research	Augments the external validity (generalisability)
Opportunity to study several contexts within the case	
<i>Disadvantages</i>	
Limits the generalisability of the conclusions	Often limits the depth of the study due to resource constraints
Greater chance of misinterpreting a single event and/or exaggerating an event	Requires more resources

The bottom line is that a single case design is a well-accepted research design in operations management, as exemplified by the editorial (an excerpt provided below) of a special issue on case study research, in the *Journal of Operations Management*, one of the premier journals in operations management.

For this special issue, we suggested that articles could be based on one or several case studies, or a full field study and could include qualitative and/or quantitative analysis of data. The studies should be rigorous in their approach and methodology and explicit in their articulation of the new insight, the rich illustration of a concept, or the hypotheses being generated.

(Meredith & Samson, 2002, p. 415)

5.2.1.3. Rigour

Given that the propose of the study (more precisely, the second phase of the overall study) is exploration, the traditional positivistic quality criteria of rigour—construct validity, internal validity, reliability, and generalisability/external validity—does not strictly apply to this particular phase of the study (see Beverland & Lindgreen, 2010). However, the researcher attempted to establish construct validity of the factors that emerged (the drivers and restraints that apply when Taguchi methods are actually being introduced in a mature Lean environment in the apparel industry) through triangulation—that is, use of multiple methods and multiple sources of data and ethnographic engagements (details follow). Although the researcher used a single case design, which prevented her in using the replication logic to augment external validity/generalisability, she chose her case (subject) carefully and specified her population (mature Lean organisations in apparel manufacturing) correctly, to give the best chance for her findings to become generalisable.

A general description of multiple data collection methods used by the researcher to complement the quantitative data derived from her RPD experiments are mentioned below (the details are given later).

Participant Observations

Participant observations is a data collection method that is frequently used by social scientists and anthropologists to observe and comprehend the tacit and explicit aspects of the culture of a group of people, by way of interacting with them over an extended period of time (DeWalt & DeWalt, 2010; Flynn et al., 1990). Due to the extensive interaction involved, Flynn *et al.* assert that participant observation is viable only for a

single case study in operations management research—an example, which somewhat parallels parts of the study conducted by the researcher, is the study conducted by Runcie (1980), where he spent five months as a line employee in an automobile production line to understand worker feelings on automobile assembly line operations.

Interviews

Flynn *et al.* (1990) as well as Yin (2011) define two types of interviews: structured interviews and ethnographic interviews. Structured interviews are based on specific questions, although some questions can come based on the direction the conversation (between the researcher and the informant) is heading. Ethnographic interviews on the other hand start from general questions and gradually progress towards questions that discover more concrete ideas, as the observer learns more about the phenomenon being observed. As such, ethnographic interviews are nearly always unstructured (Yin, 2011).

Secondary Data

In social science research, secondary data refers to data collected by a researcher using sources that were not initiated by the researcher (Creswell, 2014). McDonald and Eisenhardt (2014) asserts that secondary data can be used as supplementary data to enhance the validity of the findings of case study research.

5.2.2. Lean Journey of the Case Study Organisation

Case study organisation (the factory in which data were collected was part of it) embraced Lean manufacturing in 2004, that is, exactly after 17 years since it was formed in 1987 by three visionary founders who always wanted to create a company that is strategically differentiable, in terms of product and market positioning, by exploiting what is known as the “first mover advantage” in strategic management (Lieberman & Montgomery, 1988; Suarez & Lanzolla, 2007). In terms of product positioning, the organisation ventured into manufacturing high-end intimate apparel for women (which was new to Sri Lanka at the time), and thereafter, active wear (sports/leisure) and specialised fabric. In terms of market positioning the company’s strategy is to create strategic partnerships in both the upstream and downstream of the supply chain. In addition, improving supply chain efficiency via internal production efficiency and faster turnaround times is also a strategic objective of the organisation. According to their

visionary leader (the eldest of the three brothers, who is the chairman of the organisation) turning to Lean manufacturing was a natural choice as far as his organisation is concerned because “empowerment” has always been something that sets this organisation apart from the others.²³ The organisation is used as a case study on operations management, corporate social responsibility, and empowerment by leading business schools and corporate bodies in the US (e.g. Harvard Business School, Stanford Business School, World Bank) and Europe (e.g. London Business School, Copenhagen Business School).

The organisation acquired the so-called Lean knowledge in two primary ways: through consultants and through intensive overseas site visits by the senior leadership team. In regards to seeking expert assistance, the organisation hired experts who have previously worked in Toyota/Ford’s joint venture plant in Kentucky, USA; they also sought help of some researchers of University of Kentucky, who were specialised in Lean manufacturing. In regards to site visits, initially, as many as 25 senior and middle level managers visited a representative sample of Toyota’s manufacturing plants in Japan over a period of 3 weeks to understand shop floor and supply chain practices in connection with the TPS. In addition, the chairman of the organisation, who is a qualified chemical/process engineer, visited Japanese organisations in the fashion industry (e.g. luxury mattresses) to study how such industries adopt the TPS to suit unique needs of the fashion industry. The middle level managers played a vital role in teaching Lean principles and practices to lower level managers and floor-level workers. However, the organisational change required to embrace Lean was always being driven by the top managers.

According to the organisation, it took four years to mature in Lean manufacturing. The new recruits of the organisation at all levels of the operation have to undergo a training programme that provides basic knowledge on Lean. The training covers aspects such as 5S, visual management system, and Kanban. The organisation uses on the job training as the primary method of educating the employees on the organisation’s own Lean manufacturing system (i.e. the XOS). In addition, the organisation uses workshops and class room type training programmes on specialised topics such as Kaizen, and

²³ The details of empowerment, such as the name of the empowerment scheme for women, are not disclosed to prevent the identity of the organisation.

Yamazumi. The employee training of the organisation is designed to improve both employee productivity and employee retention.²⁴ The three divisions of the case study organisation (intimate apparel, active apparel, and specialised fabric) frequently cleans up many international awards. Some of these include IIE's Lean Best Practice Award (awarded by the Institute of Industrial Engineers, USA), Asia's Best Employer Brand Awards for Human Resource Strategy, Victoria's Secret's Vendor of the Year Award, the Taiki Akimoto 5S Award, the Global Organic Textile Standards (GOTS) Award, and Excellence in Social Responsibility Award for Women's Issues (awarded by the American Apparel and Footwear Association).

Introducing the Case Study Factory

Case study factory from which the data were collected by the researcher is one of the first apparel plants in which XOS was implemented by the case study organisation. This factory puts every effort to reduce waste and nonvalue adding activities from its value chain. Thus it serves as a role-model for the intimate apparel division of the case study organisation as well Sri Lankan manufacturing organisations in general (particularly in apparel manufacturing). According to the case study organisation, they began their Lean journey by changing the mind-set of the workforce. This included creating a rewards and recognition system that is commensurate with Lean and productivity improvement. The physical appearance of the factory (e.g. the layout) was changed subsequently as a part of implementation of their sociotechnical system. The case study factory has now become the knowledge hub for Lean Manufacturing within the case study organisation.

The case study factory, as mentioned earlier, is one of the 31 factories belonging to the Lean organisation based in Sri Lanka (this organisation has several factories in India, Bangladesh, Indonesia, and China and design offices in New York, Hong Kong, and UK). The case study factory has a production capacity over 30.5 million pieces of

²⁴ Retaining female employees in a factory (the apparel manufacturing industry is dominated by female employees) is a monumental challenge in developing countries. Many women (not so much in the case study organisation) quit their job when they marry (due to cultural reasons), although few of them return after raising children. The education programme for the female frontline staff of the case study organisation goes beyond training them on Lean practices. The case study organisation uses its training programmes on Lean also to simultaneously develop English language skills and computer literacy of its female frontline staff, in order to prolong their tenure in the organisation.

garment per year. The factory contains 94 manufacturing modules²⁵ operating in two shifts (from 06:00 AM through to 02:00 PM and from 02:00 PM through to 10:00 PM) with a total head count over 1940 personnel.

The case study factory great gains as it matured in Lean operations. Table 5.2 depicts the operational improvements the case study factory achieved by implementing Lean over a period of 5 years.

²⁵ A manufacturing module is a collection of people and machines dedicated to perform a key operating task such as cutting and sewing. Sewing modules are described in detail later.

Table 5.2: The Operational Improvements the Case Study Factory Achieved by Implementing Lean Over a Period of Five Years – from 2008 to 2012

Sr	Area of Improvement	Previous	Now	Comments
1	Fabric and elastic unloading	8 hrs	3 hrs	Batch wise segregation packing method by the supplier
2	Quarantine and batch segregation	20 hrs	8 hrs	Unloading direct to the bins except for pacific deliveries, (Issue with the pacific has not been solved)
3	Inspection	10 hrs	0	No raw material inspection
4	GRN process	5 hrs	2 hrs	Same textiles from the supplier is uploaded to our system
5	Loading to raw material bins	5 hrs	3 hrs	Directly to the bin
6	Stock holding	22 days	9 days	Milk run , supplier alignment
7	Pick and issue to sub stores	8 hrs	0	Directly to the immediate supplier
8	Stock holding sub stores	3 days	0	-
9	Issuing to modules and cutting	60 min	20 min	Scanning
10	Fabric rolls available in cutting	5 hrs	75 min	Min max available in the cutting for AM
11	Layering	60 min	65 min	
12	Cutting	2 hrs	2 hrs	
13	Bundling	120 sec	30 sec	
14	As cutting work in progress	2 ½ days	5 hrs	Common work in progress, pull system, Kanban
15	AQL inspection at cutting	30mins	0	
16	Non-embellish parts available in the cutting	5 hrs	4 hr	
17	Cut panels available in the line in	10 hrs	1 hr	
18	In line production work in progress	8 hrs	30 min	
19	Hourly AQL inspection	3 ½ hrs	40 min	
20	Final AQL inspection	15 hrs	0	
21	Move to finished goods from AQL	15 min	15 min	
22	Completion of partial carton at finished goods	10min	0	
23	Storing at finished goods	09 days	6 days	
24	Pasting stickers	1 min	30 sec	
25	Finished goods loading to container	5 hrs	2 hrs	

Table 5.3 shows the commonalties and differences between the TPS and the XOS.

Table 5.3: Comparing and Contrasting XOS with the TPS

Sr	Elements Common to both TPS and XOS	Elements Unique to XOS	Elements of TPS that are not Shared by XOS
01	5S	6S	
02	Training		
03	Kanban/ Pull production system		
04	Preventive maintenance		
05	Cellular manufacturing		
06	Visual control system		
07	Kaizen/ Continuous Improvement		
08	VSM (Value Stream Mapping)		
09	Cross functional teams		
10	Setup time reduction		
11	Strong supplier relationships	Some suppliers have located their branches inside the factory to manufacture items such as labels and price tickets; these suppliers produce items that are necessary for all styles of products.	High supply chain integration; XOS is constrained by the supply chain (especially the customer side of the value chain) whereas TPS is a supply chain wide value adding system.
12		5 pieces flow (small lot size)	One-Piece-Flow
Notes:			
<p>(i) The researcher used personal observations, training manuals used in the factory and other documents to conclude that the XOS has the elements mentioned above. The elements of the TPS are based on Hopp and Spearman (2011) and Liker (2004).</p> <p>(ii) The XOS has a 6th S, on top of TPS's 5S. The 6th S is "Safety".</p>			

As with the TPS, quality is a major element in the XOS. Therefore, the factory (and its sister factories elsewhere) strives to improve their quality in every aspect of its operations. With regard to product quality, the quality assurance is achieved through inspection and product screening at various stages of the production process. Figure 5.1, 5.2, 5.5, and 5.6 depict some operations that take place in the factory.

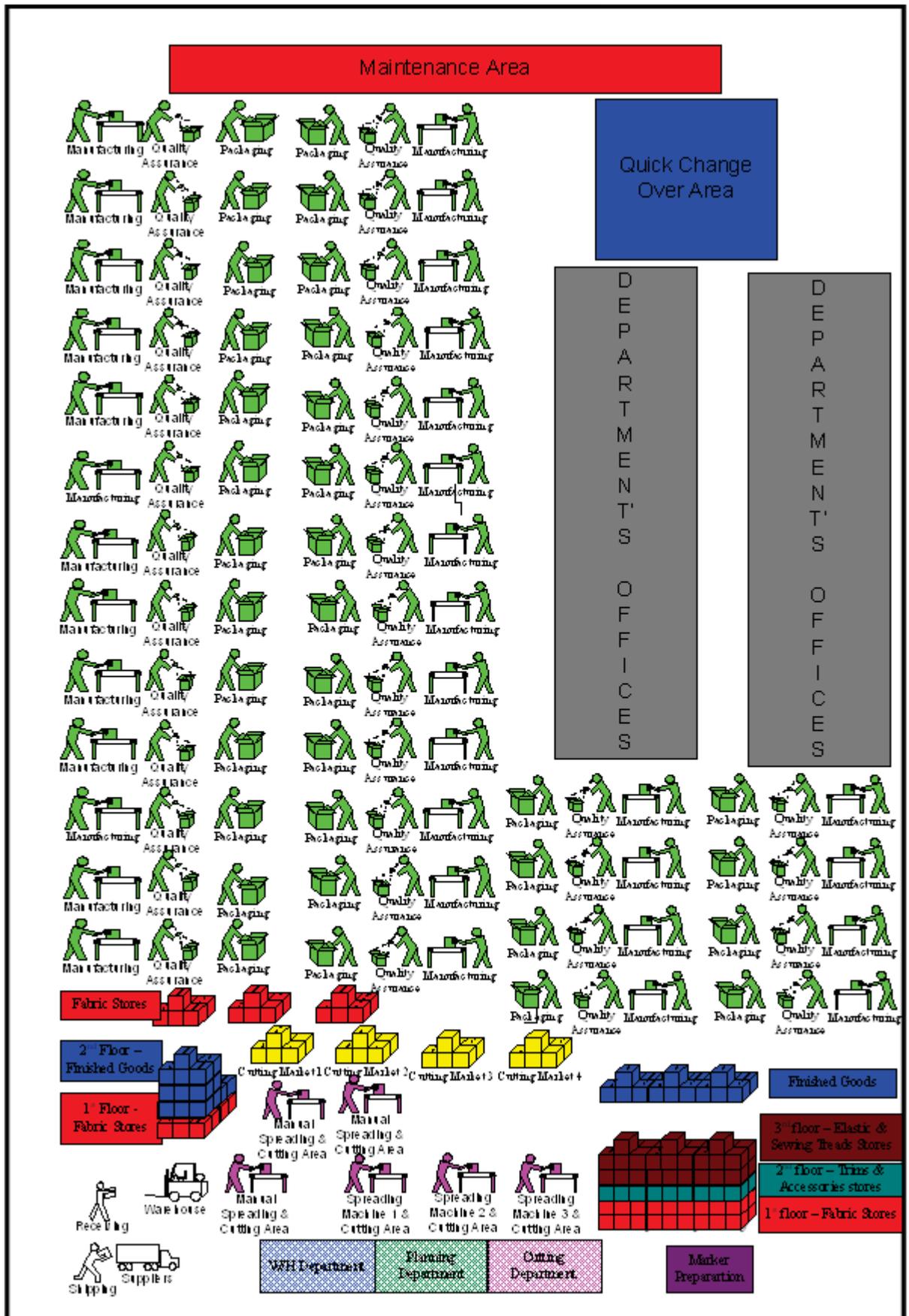


Figure 5.1: The layout of the factory (Source: factory records)

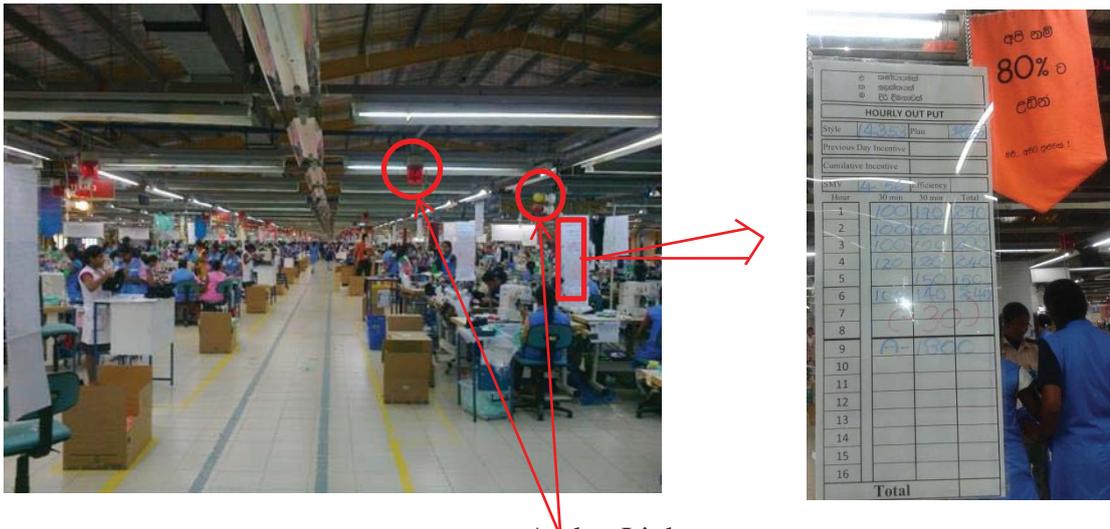


Figure 5.2: The factory shop floor Andon Lights

5.2.3. Overview of the Operations at the Factory

The description below provides the details of the production operation at the case study factory. The factory can be viewed as a collection of interconnected process that transforms fabric into wearable garments. In keeping with Lean, the operating system (XOS) of the factory is designed to gain maximum productivity whilst assuring quality of products and services. The factory receives raw material from both local and overseas suppliers. After receiving the material, they are stored in a warehouse until being collected for production. The factory uses an integrated information system to signal its suppliers when and in what quantity incoming material is needed. This is to keep their stock levels as low as possible as keeping unnecessary inventories results in waste (Lander & Liker, 2007; Liker, 2004). Detailed quality assurance (QA) procedures (the details vary depending on the type of incoming material) have been put in place by the factory for incoming supplies to ensure that nonconformities (defects) will not be carried forward to the finished product. Once the incoming material passes the QA tests, they are accepted and transferred to the production operations. The production operation is phased into three main levels: cutting, sewing, and finishing.

Cutting is the initial process of converting fabric into finished pieces for sewing. The cutting plan is prepared according to the Master Production Plan. If the production batch size should consist of N number of pieces from a particular design (consisting of various sizes), the cutting department determines the number of layers of fabric they need to be cut (simultaneously) to produce the various components (e.g. front, back,

gusset) of the production item (e.g. underwear); for most types of fabric, the number of layers should be less than 50 as the cutter cannot handle (go through) more than 50 layers of fabric at a time. The factory uses computer aided design (CAD) technology to draw the marker (a lengthy sheet containing the drawings (the plan view) of different pieces of the item) that will be laid upon the top layer of the fabric at the time of cutting (the width of the marker is made equal to the width of the fabric).

Release of fabric from stores to the cutting department is done after submitting the cutting docket, which are prepared by considering the cutting capacity and production requirements. Before commencing the cutting operation, the fabric is relaxed to minimise shrinkage, before and after sewing the garment. An important quality procedure in laying the fabric is to ensure that all pieces for any given finished product (e.g. front piece, back piece etc.) are cut from the same fabric roll. This is to ensure the minimum within garment fabric colour variation; the factory is so customer focused they would not cut different pieces of fabric to sew a piece of garment from different rolls of fabric as any between fabric colour variation (however small that could be) could affect the customer perception on product quality. To facilitate selecting the same fabric roll, tissue paper separators are inserted in between fabric roles to minimise the chance of mixing up fabric. Semi-automatic cutters are used to cut the pieces of fabric exactly on the lines printed on the marker and all the layers are held together firmly with the help of clamps to prevent any relative sliding during the cutting process. If there is any special request from the buyers, embroidery and screen printing are processed. These operations are nearly always sub-contracted to trusted business partners who are specialised in those services. Finally, the cut panels are bundled together and stored to be issued to production modules using the kanban technique.

Cut fabric are passed to the production area for the sewing operation—the heart of the whole factory. The sewing operations are organised in manufacturing (sewing) cells in keeping with the assembly-line concept. A sewing cell is called a module. Forty-seven sewing modules have been set up in the factory in a layout that maximises production efficiency. Each module does produce a complete product (garment) although typically, not all 47 modules produce the same design at the same time. Machine settings are adjusted (set) based on the product style number or the essential features of the garment (e.g. fabric type). Each module at the factory consists of 18 machines on average, being

handled by 26 personnel (on average) including the module's team leader, who checks and guides the operators. Keeping records, achieving the target plans of the module are some of the primary responsibilities of the team leader. The factory is continually looking to optimise people utilisation. The sizes of the modules (in terms of operators used) have been reducing steadily since the organisation turned to Lean in year 2004. At the time of the researcher conducting the fieldwork, the factory has been having as many as 8 modules containing as few as six operators (per module) to manufacture a whole piece of garment—something that is unparalleled in the industry of similar scale. The factory was in the process of downsizing (in terms of number of operators being utilised) the remaining modules also, based on the successes they have been having with the smaller modules. Another salient feature of the factory is that there will always be a pilot run preceding the production run proper.

The factory is also very adept in using the tools and techniques at lower-level manifestations of Lean. For example, the factory follows the 5S standard to the better²⁶. According to the training department, 5S (Figure 5.3) is taught to the operators at the very early stages of their training as 5S is embedded in the factory's culture; as mentioned earlier workplace safety is added to 5S as the sixth element in the factory's operating system.

²⁶ The acronym 5S stands for the five Japanese words (approximate English translation in parenthesis): Seiri (Sort), Seiton (Straighten), Seiso (Shine), Seiketsu (Standardize), and Shitsuke (Sustain). As basic as it may be, 5S has a deep rooted meaning in Lean/TPS (Chapman, 2005; Kulak, Durmusoglu, & Tufekci, 2005).



Figure 5.3: Display of the workplace standardisation procedures

The factory also adheres to the “visual industry” concept in Lean to facilitate communication. For example, the daily performance and related data of each team are displayed live during the operation. Since the data include recent historical data, in addition to latest data (Figure 5.4), the front line staff and their team leader would take immediate action if any unusual patterns (e.g. downward trends, high rejection rate) do immerge. Technically, this is taking action for special cause variation. The researcher observed that control charts are not being used in the factory as a matter of routine to understand variation. Discussions with the quality manager revealed that it is difficult to use control charts in the factory due to the large number of product items being produced in the factory.²⁷ Frequent style/design changes by the customer also compounds the problem. For this reason, the researcher realised that the staff (team

²⁷ In order to use control charts, the quality department has to first calculate control limits (and the process centre) based on sample data (this is typically known as phase 1 control charting). Then (phase 2) they have to use these calculated control limits to monitor the process (Wheeler & Chambers, 2010). If the machines have to be set for different styles frequently, it becomes difficult to use control charts because the process variability (hence the control limits), whether it is the variability of the throughput/performance or the variability of a quality characteristic of the product, depends on the particular item being produced.

leader) interpret the running record of data much the same way as a person would use a run chart to interpret the data in an intuitive manner.

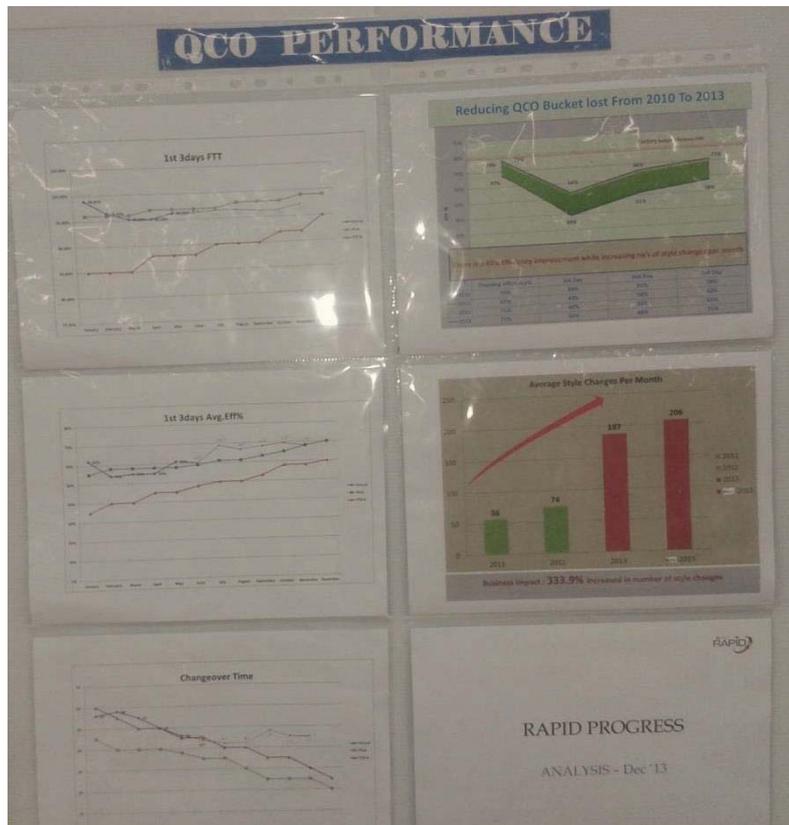


Figure 5.4: Display of performance

At the end and the middle of each line, checking of pieces takes place; the checks are performed to identify assembly/sewing problems, non-conformance to product specifications (Figure 5.5), and broken seams. If any defect is found, an alteration sticker is placed on the garment and sent back to the relevant operator to whom the problem belongs to, as judged by the team leader. During the sewing operation in each module, all workers conduct in-line quality inspections (Figure 5.6) whilst conducting their sewing activities to assure the quality of final product in an efficient manner. There are no separate quality checkers and the total responsibility of conformance quality²⁸ lies with the operators. Therefore, ‘autonomous work groups’ are another Lean feature adopted in the factory.

²⁸ Product quality contains two facets: the quality in the product’s design (known as design quality or quality of design) and quality in being able to conform to specifications (known as conformance quality or quality of conformance) (Meirovich, 2006).



Figure 5.5: Inline quality inspection



Figure 5.6: Checking the waist measurement for conformance to specifications

Final phase of the garment manufacturing is finishing and packing process, where price tickets are attached to each of 30 pieces of completed garments, before being packed into polythene bags. Garments are tagged, sized, and packaged according to customer specifications. Filled cartons are then moved to the finished good area after pasting a barcode sticker followed by a scan. Finally, the packed products are shipped to buyer distribution centres through the finished goods department after passing acceptable quality level (AQL) inspections; thus all cartoons shipped to the customer do carry the “AQL OK” sticker. Another feature of autonomy in the factory is that the responsibility of the AQL inspection is passed on to the respective teams or modules (the packaging is

done only after the AQL inspection). In regards to briefs alone; the factory produces more than 200 styles in a year in large quantities.

5.2.4. Conformance Quality Issues

In spite of being a Lean organisation and in spite of using the state of the art in cutting and sewing, the factory is not without conformance quality problems from time to time. Since the aim of the company is to maximise customer value by increasing the perceived worth of the product and reducing the cost by eliminating waste, significant quality problems of any product line defeats this Lean objective (Hines et al., 2004) because the factory produces product lines in large numbers. At the time of launching the researcher's fieldwork a substantial nonconformity problem the factory was struggling to come to terms with excessive variation in one of its new styles of women's briefs (a type of Thongs; style # 12875). The factory staff's keenness to solve this variation problem triggered the researcher's fieldwork to study how the RPD method fits to the Lean apparel industry and thereby answer her third and fourth research questions and the associated research objectives. The fieldwork was carried out between the beginning of August 2013 and the middle of December 2013 (approximately 18 weeks).

5.3. LAUNCHING THE FIELDWORK

There were two fieldwork components in the study: data collection for answering the third research question (wave two of data collection) and data collection for answering the fourth research question (wave three of data collection). Figure 5.7 below shows the time line for data collection of the whole study.

Activity	July 2013	Aug 2013	Sept 2013	Oct 2013	Nov 2013	Dec 2013	Jan 2014
1st wave of data collection: distributing the survey instrument to 31 factories (answering RQ2)							
2nd wave of data collection: fieldwork related to understanding the variation problem/s and conducting RPD experiments (answering RQ3)							
3rd wave of data collection: fieldwork related to understanding the drivers and restraints in implementing RPD designs (answering RQ4)							

Figure 5.7: Time line of data collection including fieldwork at the case study factory

5.3.1. Breaking the Communication Barrier

In spite of being a woman and in spite of being a Sri Lankan with approximately the same age as an average machine operator in the factory (most of the machine operators in the garment industry are women and this factory was no exception (Arsenault, Rose, Azulay, & Meyer, 2009; Safa, 1981), establishing communication with the frontline workers was not an easy task; this will always be the case in Sri Lanka at the best of times, due to the social system prevailing in that country; one such oddity is the enormous respect (which translates to a class gap) the engineers and doctors receive from the general public; as Sri Lanka is now moving towards a medium income country, things are beginning to change.²⁹ The researcher realised at the very outset that the operators were at unease as they started calling the researcher “*engineer madam*” to signal that there is a social status difference between them and the researcher. Because the researcher was external to the factory and because researcher is with a production engineering background, the machine operators were also somewhat circumspect initially about the motives of the researcher (the operators quickly realised that the researcher was not looking at individuals and their productivity, which also settled their nerves).

Given the vast amount of time the researcher has to engage with the frontline workers in conducting her fieldwork, the researcher’s first priority was to break the communication

²⁹ In October 2013 the government banned displaying stickers “doctor” or “engineer” on car windscreens as such vehicles get rarely checked or searched by the police, leaving criminal elements to take advantage of the VIP status accorded to doctors and engineers by the general public and the police (Lanka C News, 2013).

barrier. This started by getting the researcher trained voluntarily—with the full support of the factory management in each key department (particularly cutting and sewing departments) on the operations, alongside the frontline workers over a period of four weeks (24 days to be precise). During this period the researcher told the operators in the sewing department that she is looking for some volunteers to conduct one or two experiments with the sewing machines. This was the first signal the researcher sent to the workers that she is not there to find fault with the people. Nearly always the communication between the researcher and the frontline workers during the 4-week training period (referred to as orientation training from here onward) was informal. The researcher ensured that she called the frontline workers by their first names. As it became clear to the frontline workers that the objective of the researcher’s study is to understand the system that shows variation and not the productivity of individuals, and therefore, the researcher is in fact a facilitator (more precisely, the person who provides technical input to the work improvement teams that are involved with the variation problem) in their day to day activities, the phrases that they used to address the researcher started to change. Instead of using salute-laden phrases such as “engineer madam”, the frontline workers became at ease in using salute-neutral phrases such as “you” and “Pramila miss” to address the researcher; these and other gestures signalled (in the Sri Lankan cultural context) that the frontline workers are willing to cooperate (the researcher received fullest support from the factory management right from day one). The next section provides a summary of all the fieldwork carried out by the researcher in answering her third and fourth research questions.

5.3.2. A Summary of Field Activities

Table 5.4 provides a concise summary of field activities conducted by the researcher along with the purpose of each activity. Communication with frontline workers (formal and informal) was done in the native language (Sinhala), while formal communication with the senior managers was done in English (the usual practice in the Sri Lankan culture as frontline workers in general cannot communicate in English meaningfully). When there was formal communication with both frontline workers and manager/s together (e.g. brainstorming) the communication was done in the native language.

Table 5.4: A Concise Summary of Fieldwork and Justification

Sr	Activity	Number of Personnel	Approx. Time Spent(hrs)	Purpose
1	Orientation training		150	To familiarise with the critical operations and the activities; break communication barriers; to familiarise with the work culture
2	Meeting the General Manager (formal)	1	1	Welcoming the researcher, introduce the key staff and informally discuss the researcher's aims and objectives related to her fieldwork. The initial briefing of variations problems (the plant manager was also present) to the researcher; to brief the manufacturing performance over the last five years to the researcher
3	Meetings and discussions with the Plant Manager (formal)	1	2	To further discuss the current major variation problems and their impacts; to provide an overview about RPD approaches to the plant manager; to understand manufacturing performance over the last five years (collection of records)
4	Meeting and discussions with the Planning Manager	1	2	To know the existing problem solving approaches used in the factory; to provide an overview of the RPD approach and get his initial reactions for its suitability for the factory (e.g. as a machine parameter setting method)
5	Meeting and discussions with the Human Resource Manager and the Assistant Manager	1	5	To discuss the human resource planning processes (labour needs identification, recruitment, career development, rewarding and punishment etc.); to discuss employee relations (trade unionism); understanding how employees respond to change
6	Meeting the Quick-Change-Over (QCO) Manager	1	1	To get an understanding about the performance of QCO activities; to identify the existing major issues or problems in QCO
7	Meetings and discussions with the Quality Manager (formal and informal)	1	8	To get further understanding of the inherent variation problems; to discuss how variation issues are currently dealt with (e.g. understanding the tools and approaches being used); to get the initial reaction and subsequent reactions (post hoc) to RPD approaches; to understand the existing quality improvement approaches being used; to get the problem solving team moving (e.g. facilitating in root cause analysis)

Sr	Activity	Number of Personnel	Approx. Time Spent(hrs)	Purpose
8	Meetings and discussions with the Work-study Manager (formal and informal)	1	8	To get initial and subsequent reactions about the suitability of RPD approaches; to further refine the definition of the critical variation problem; to collect additional data on the manufacturing performance of the past five years; to discuss how workers react to change (collect examples of positive and negative reactions)
9	Meetings and discussions with Assistant Production Managers (formal and informal)	3	12	To identify the current variation problems in the production; to get idea about RPD approach; to understand the existing problem solving approaches; to discuss how workers react to change (collect examples of positive and negative reactions)
10	Meetings and discussions with the Mechanics (formal and informal)	10	40	To get familiarised as to how mechanics go about in changing (adjusting) machine settings; understanding the existing approaches to reduce the variation problems and the role the mechanics play in these activities; to get help in conducting the experiments (to physically change the factor settings for each run based on the run pattern in the design matrix); to uncover the issues based on their knowledge and experience (mechanics were a part in brainstorming activities)
11	Meetings and discussions with the Team Leaders (formal and informal)	15	50	To identify the key variation problems; identify the key factors based on their experience; to get their opinion about existing problem solving approaches; brainstorming activities
12	Meetings and interactions with the Machine Operators (formal and informal)	100	180	To assess the operators' understanding on key factors that affect the variation of specific quality characteristics; to evaluate the support the operators get from the factory's top management for their personal growth; socialisation (the researcher spent about 50 hours of her time to convince the operators that she is not there to act as an inspector inspecting how each worker performs); brainstorming activities (note that only about 5% of the operators were actually involved in formal brainstorming activities); to help the researcher in conducting studies on the measurement system (Gauge R&R studies), process stability and capability analysis; to perform actual sewing during the course of the experiments to enable the researcher to record the results for each trial

Sr	Activity	Number of Personnel	Approx. Time Spent(hrs)	Purpose
13	Meetings and discussions with the AQL Auditors	2	5	To understand the existing quality issues and existing problem solving approaches; to understand the existing statistical quality control procedures; to understand the level of the current state of product quality and how these levels compare with those of the competitors
14	Meetings and discussions with the Quality Controllers	10	30	To understand the existing measurement system and measurement procedures; to identify the major quality issues; to understand the existing approaches used to solve quality issues; to collect data on nonconformities and their consequences (quality rejections rate, waste, rework etc.); to understand the existing statistical quality control procedures
15	Meeting the Members of the " Lean Team "	3	20	To understand the existing problem solving approaches, tools and techniques being used; to identify the key factors that affect for the specific variation problem (variation of the back-coverage measurement)
16	Meeting a Specific Fabric Supplier	1	0.5	To understand how the factory (and its sister factories) interacts with the supplier
17	Meeting the Assistant Quality Manager	1	3	To understand the raw material inspection procedures; to understand the supplier relationship management processes; to understand and collect data on CI made by the organisation over the past five years; to understand the variation (noise) transmitted from raw material variability
18	Researcher's personal observations		100	To inspect standardisation procedures; to study the use of visual controls management; to witness a sample of training and development programmes and activities for new and established employees; to witness how preventive maintenance is being done; to observe how activities are being organised and done in the factory (understanding the culture and climate of the factory)
19	Document inspection		50	Verifying the validity of responses given by the respondents for specific questions by inspecting reports (AQL reports, customer feedback reports, worker performance charts etc.); to independently verify the frequency of use of quality tools, techniques and procedures (e.g. Pareto Charts, PDCA charts, fishbone diagrams, five whys analysis etc.)

Sr	Activity	Number of Personnel	Approx. Time Spent(hrs)	Purpose
	Total time spent on data collection (approximately)		580	
Note: The 19 activities mentioned above were not necessary mutually exclusive; for example, activity # 18 was done in parallel with several other activities mentioned above.				

5.3.3. Comprehending the Variation Problem

Since variation can manifest in many ways—as variability in the measurement/s (variable) of a quality characteristic/s or variability in the product attribute/s (e.g. defects)—the key is to comprehend the nature of variability (Box & Bisgaard, 1987; Nolan & Provost, 1990; Wheeler & Chambers, 2010) of a product item that returns a high nonconformity rate, with the help of the operating staff. Such a nonconformity issue, particularly if the product is of high value, can be considered as a substantial quality issue faced by the company.

As mentioned earlier (section 5.2.2), at the time of launching the fieldwork (see Figure 5.7 for the timeline), a quality improvement team in the factory, consisting of nine members (2 machine operators, 2 team leaders, 1 AQL auditor, 1 quality controller, 1 quality executive, 1 production technical trainers, and the quality manager) have been grappling with nonconformity issues of a particular new design of Thongs manufactured for their customer (Victoria’s Secret, San Francisco, CA, United States); the product (sold at a wholesale price of US\$ 9.50 per item at the time of conducting the experiment) is a high value item produced for fashion houses. The aforementioned quality improvement team have been searching a solution (not very successfully) for 20 weeks when the researcher launched the fieldwork towards solving the problem, using RPD methods. The researcher’s role was to act as a facilitator for the quality improvement team by providing the technical knowhow to widen the team’s problem solving capability. This was deemed as the appropriate approach to collect data to achieve the research objectives (the quality manager continued to lead the team and the researcher continued to act as the facilitator). The team received fullest support from the general manager and the plant manager.

Inspection of nonconformity reports and discussions with the quality improvement team led to the identification of three nonconformity issues:

- (i) A sizable number of back-coverage measurements (in parts per million) of the particular product go outside the specification limits (the process capability analysis results in Chapter 7) (*this was the most critical nonconformity issue*);
- (ii) The stitch density (the number of stitches per inch) on both the right hand side (RHS) and the left hand side (LHS) of the leg hem are not consistently uniform as some areas of the leg hem receive more stitches than the other areas (*this was a moderately critical issue*), and
- (iii) “Roping”³⁰ occurs in some of the garments (*this was the least critical issue*) with no apparent special cause.

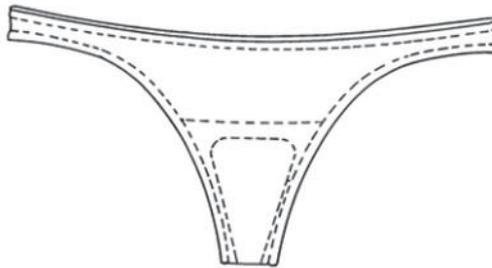


Figure 5.8a: Front view of the Thong style garment

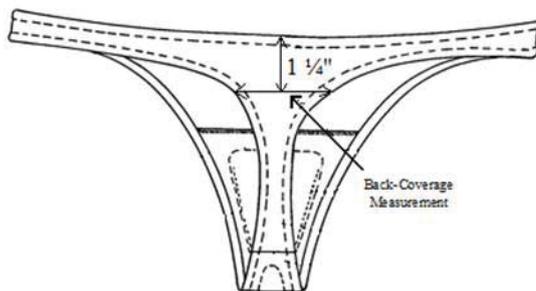


Figure 5.8b: Back view of the Thong style garment

³⁰ Roping is a product nonconformity that occurs due to twisting of the fabric while sewing. Roping occurs due to the very narrow width of the back side of the product (Figure 5.8b), which makes handling of the product quite challenging (the fabric material was also taken as a noise factor that aggravates the problem).

Figure 5.8 and 5.8b show the front and back views of the product respectively. Figure 5.8b also depicts the operational definition of the *back-coverage measurement*, the primary quality characteristic being considered in this experiment. As shown in Figure 5.8b, the back-coverage measurement is taken 1 ¼" from the top of the waist. The specification for the back-coverage measurement of the garment, specified by the US customer, is 1 7/8" ± 1/4.

The primary objective of designing an experiment was to reduce the process variability of the back-coverage measurement while keeping its expected (average) value as close as possible to its target value: 1.875". The secondary objectives were to reduce the variability of the stitch density at the leg hem area and minimise the chance of occurring roping (to reduce the average roping count as much as possible). The secondary objectives were less important to both the quality improvement team as well as the researcher.

Thus for the purpose of conducting RPD experiments, the primary objective of the quality improvement experiments was defined by the researcher: To assess the suitability of Taguchi methods on statistical grounds as well as practical grounds to handle a substantial waste reduction problem—to minimise the variability of the back coverage of the product being studied—faced by a mature Lean apparel manufacturer and compare these techniques with traditional DoE techniques in the setting studied.

5.3.4. Identifying the Experimental Factors

Having specified the primary optimisation objective, the next step was to posit the universe of potential factors that affect the variation, also keeping in mind the secondary optimisation objectives (minimise the variability of stitch density in the leg hem area and minimise roping). In keeping with Taguchi style RPD experimentation, *brainstorming* was the technique used to elicit possible factors that affect the variability (Krishnaiah & Shahabudeen, 2012; Roy, 2010).

Since the nine-member regular quality improvement group was not large enough for a brainstorming session that also required *Pareto voting* (Park, 1999), the team was augmented with additional personnel, for the purpose of brainstorming. The composition of the brainstorming team is shown in Table 5.5.

Table 5.5: The Composition of the Brainstorming Team

Designation	Role	Number of Personnel
1. Machine operators	Team member	03
2. Team leaders	Team member	03
3. AQL auditors	Team member	01
4. Quality controllers	Team member	02
5. Mechanics	Team member	03
6. Work-study officers	Team member	03
7. Quality executive	Team member	01
8. Production technical trainers	Team member	03
9. The quality manager	The leader/adviser on root cause analysis	01
10. The researcher	Facilitator and the RPD expert	01
Total		21
Note: The quality manager and the researcher did not participate in Pareto voting. They were providing high level guidance only (e.g. commenting on the adequacy of potential factors/causes, advising the team to which root/s certain causes should belong to in the cause-and-effect diagram).		

Each member of the team was issued the following instructions by the researcher:

- (i) Suggest as many causes of variability (the variability of the back-coverage measurement, stitch density in the leg hem area, and roping) as possible.
- (ii) Assign each cause to one of the 6Ms in the cause-and-effect diagram template given to you.
- (iii) Use the abbreviation Y1 for causes, that in your opinion, affect the variability of the back-coverage (the most important issue). Similarly use Y2 for causes of stitch density variability (leg hem) and Y3 for causes of roping; it is quite possible for the same cause to affect the variability of more than one effect (e.g. you may mark Y1, Y2, Y3 against the same cause if you think it causes all three effects: back-coverage variability, stitch density variability, and roping).
- (iv) Pass on your cause-and-effect diagram to the quality manager when you have finished.

- (v) Revise (attempt to add more causes) the cause-and-effect diagram passed on to the team members by the quality manager, after the first round of deliberations.
- (vi) Pass on the final cause-and-effect-diagram through to the quality manager.
- (vii) Vote in favor of the causes that the quality manager and I distribute to you as the team's final list (you are free to vote for any number of cause candidates); again use Y1, Y2 and Y3 notation to indicate which cause affects which quality characteristic.

Figure 5.9 and Figure 5.10 show the final cause-and-effect diagram and the Pareto diagram respectively. In the process of conducting brainstorming, majority of the team members (eleven of them) indicated to the researcher that it is difficult to isolate causes for one particular effect (e.g. back-coverage variability). Hence the researcher's requirement of members having to use the Y1, Y2 and Y3 notation to indicate which cause affects which effect was not pursued. This was not seen as an impediment for conducting the RPD experiment.

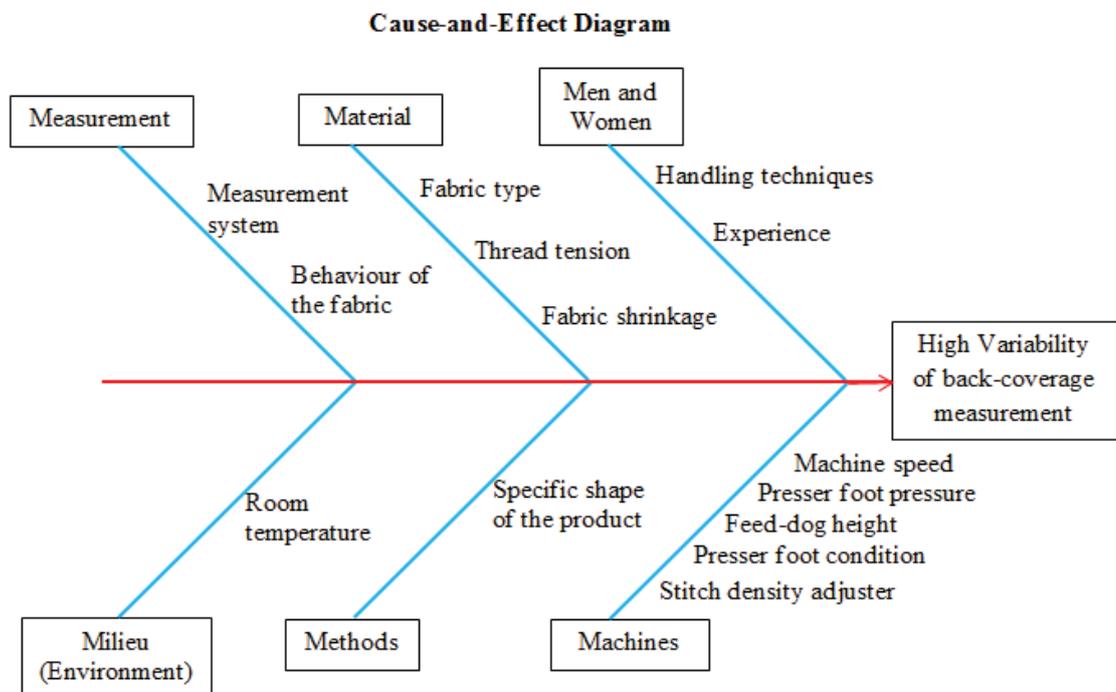


Figure 5.9: The cause-and-effect diagram for high variability

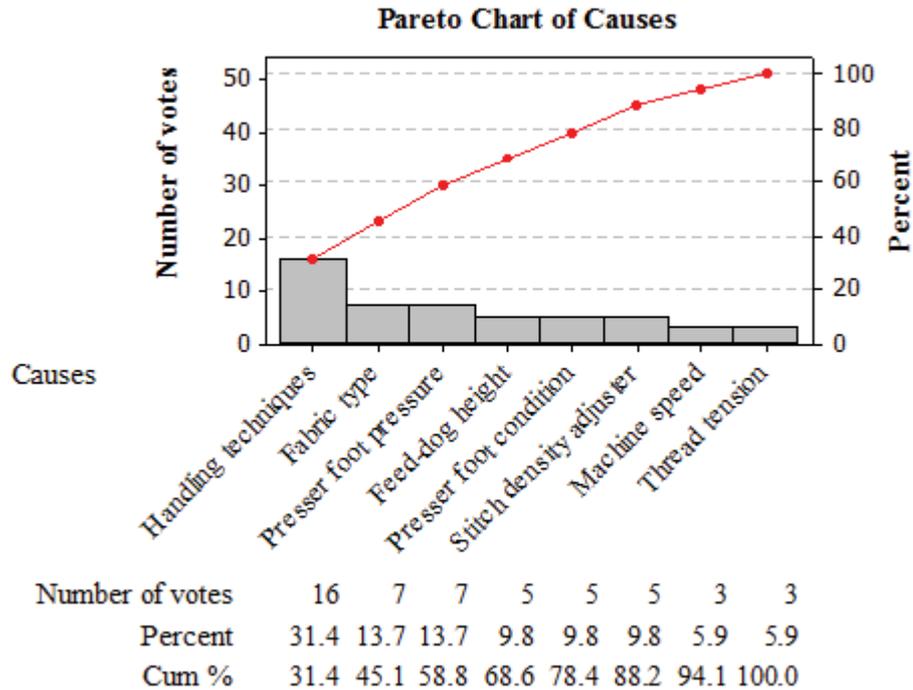


Figure 5.10: The Pareto diagram for high variability

The Pareto diagram based on 19 voters (Figure 5.10) shows that the Handling technique (operator skill), Fabric type, and the Presser foot condition (new versus heavily used), the Feed-dog height, Presser foot pressure and Stitch density adjuster (in terms of adjusting the stitches per inch – SPI) were identified as factors (six factors altogether) that have the highest potential to contribute to variability of the back-coverage (primary response variable Y1), stitch density (secondary response variable Y2, which is moderate importance), and roping (third response variable Y3, which is of least importance).

The next task was to identify the control factors and the noise factors (Antony, Warwood, Fernandes, & Rowlands, 2001; Roy, 2010; Taguchi et al., 2005). Control factors are the factors that can be controlled experimentally as well as in a real process (if required) whereas noise factors are factors that are uncontrollable in normal operation but can be controlled (with some difficulty) in an experiment (Antony et al., 2001). As explained in Chapter 3 (section 3.4) RPD experiments (Taguchi-based or otherwise) seek to reduce the variability of the response variable by determining the optimum control factor setting (Antony & Antony, 2001; Roy, 2010). Using the above definition of control factors and noise factors, out of the six experimental factors, three

were identified as control factors and three were identified as noise factors as shown in Table 5.6.

Table 5.6: The Control Factors and Noise Factors

Factor Name	Control or Noise Factor?	Mostly Thought to be Related to Y1, Y2 or Y3?
Feed-dog height (adjuster setting)	Control Factor	Y1
Presser foot pressure (adjuster setting)	Control Factor	Y1
Stitch density adjuster (screw setting)	Control Factor	Y2, Y3, Y1
Fabric type (thicker versus thinner)	Noise Factor	Y1, Y2, Y3
Handling technique (operator skill level)	Noise Factor	Y1, Y3
Presser foot condition (new versus used)	Noise Factor	Y3, Y1
Note: The last column was based on incomplete data as only 8 team members guessed which cause (factor) affects which quality characteristic.		

The RPD experiment was aimed at optimising the variability of all three response variables (Y1, Y2 and Y3) simultaneously, although optimising (minimising) the variability of Y1 was the primary focus. One can wonder how reducing roping (Y3) equates to reducing the variability of roping. Since roping is a nonconformity (an attribute) it can be shown easily that (under the assumptions of Poisson distribution) reducing the average roping level (\bar{c}) equates to reducing the variance of roping ($= \bar{c}$) (Ledolter & Burrill, 1999; Wheeler & Chambers, 2010).

5.4. THE MEASUREMENT SYSTEM AND THE CAPABILITY OF THE MANUFACTURING PROCESS

Given that the primary response variable is the back-coverage measurement (Figures 5.8b) and the staff seemed to be using what looked like a very basic measurement system, it was decided to test the precision of the measurement system of back-coverage measurement of the product (Thongs), using a Gauge repeatability and reproducibility (R&R) study.

5.4.1. Verifying the Precision of the Measurement System via a Gauge R&R Study

Robust design approaches can only be used to minimise the variation in a stable system where no variation exist due to special causes. However, the total variation inherent in any system is a combination of the process (or product) variation and the measurement system variation, as shown in Figure 5.11. Understanding the measurement system variation as a percentage of total variation is important before checking the process stability and process capability because these results do get obscured by measurement system variation (Montgomery, 2009; Ryan, 2011). Therefore a Gauge R&R test was used to assess the process variation caused due to the measurement system. Repeatability is the variation that results in repeated measurements of the same measurement taken by the same operator using the same measurement gauge while reproducibility is the variation caused due to different operators taking the same measurement using the same gauge (Montgomery, 2009).

The existing method used to measure the back-coverage measurement was taking two points at a perpendicular distance (judged without using any device such as a set square) of 1 ¼" from the top of the waist at the back side of the garment and then measuring the distance between the two points by placing a measuring tape across the two marked points (parallel to the waist).

The study variation from total Gauge R&R study for the existing measurement system was 56.92% which cannot be accepted as a satisfactory level of precision of the measurement system based on the values prescribed by the American automotive industry action group (Wheeler, 2009). Also the contribution from Part-to-Part was 67.61%. Hence a third (32.39%) of variation was due to the variation of the measurement system. For these reasons it was decided to improve measurement system.

In observing how the staff measure back coverage, the researcher observed that there was not only some guess work involved (in taking two points perpendicular to the waste, which was not a straight line), but there was disturbance to the fabric (stretching), which varied from operator to operator. The researcher therefore instructed the staff to use a template (cut from plastic, having a width of 1 ¼") (Figure 5.12) to locate the two points of measurement and use a measuring device that does not disturb

(stretch) the fabric. The operators were asked to use a Vernier calliper to measure the distance between the two points, simply because it did not disturb (stretch) the fabric. The new measurement gauge that was developed to measure the back-coverage measurement was called “Gamage’s Improved Gauge”, for charting results. Consistency and accuracy of the improved measurement system is discussed in section 7.2.1.

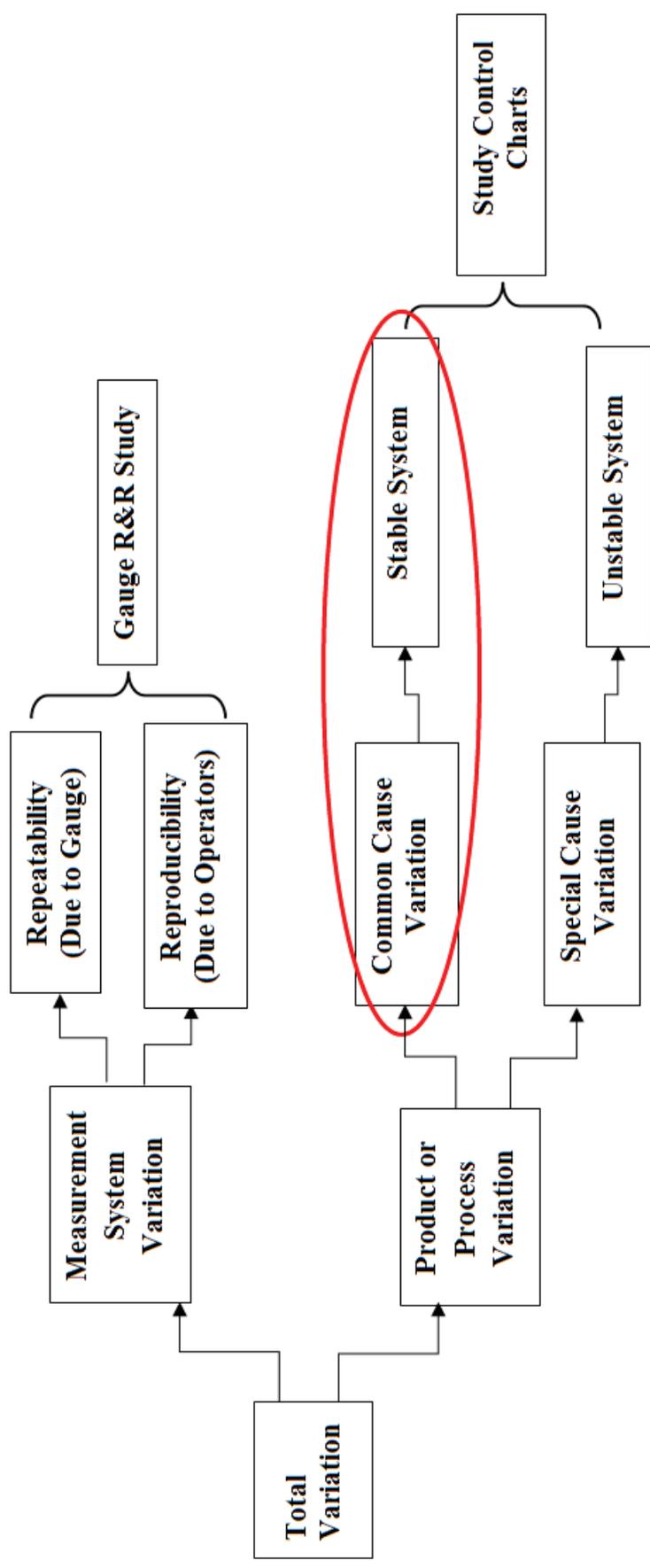


Figure 5.11: Categorisation of total variation in a system (source: Hare, 2012)



Figure 5.12: Placing the template to get the 1 1/4" of displacement from the waist



Figure 5.13: Coding the garments

Generally Gauge R&R studies are conducted with two or more operators (otherwise reproducibility cannot be assessed), with a number of samples plus a measurement gauge; the operators, the measurement gauge and the method of measurement is collectively called the measurement system (Montgomery, 2009). The study with the improved measurement gauge study was conducted using two quality controllers using 15 pieces of garments (Thongs); the Vernier calliper used for taking measurements was calibrated in inches. The 15 pieces of garments of same waist size (medium) were randomly selected from the finished good area; the finished goods are subjected to all

potential sources of process variability (machine, time, shift, job rotation). The 15 pieces of garments were coded as shown in Figure 5.13 in order to identify the measurements taken on each piece of garment.

5.4.2. Verifying Process Stability Using Control Charts

Control charts are used to visually document the process variability over time to understand whether or not the process is stable (under statistical control). A stable system shows a random variability of its output (or performance) in the control chart. If the process is under statistical control, the observations will lie within predictable limits (control limits) nearly all the time—99.74% of the time within three standard deviations from the process mean under the assumption of normality. In addition, a stable system is not expected to show any non-random patterns such trends, oscillations and long runs (Hoyer & Ellis, 1996; Montgomery, 2009; Nelson, 1984; Rao, Carr, Dambolena, Kopp, Martin, Rafii, & Schlesinger, 1996; Swift, 1995). The most well-known control charts are the control charts advanced by Walter Shewhart, commonly known as Shewhart control charts.

A number of Shewhart control charts are available for monitoring attribute data (p chart and np chart for defectives; c chart and u charts for defects) and variable data (\bar{x} and R chart, \bar{X} and S chart, and \bar{X} and MR chart). Montgomery (2009, p. 246), citing the work of Schilling and Nelson (1976) states that “sample sizes of 4 or 5 are sufficient to ensure reasonable robustness to the normality assumption”. Since the main noise factor of this study was voted as the handling technique (Figure 5.10), the frequency of change of this main noise factor (labour) was taken into consideration in deciding the sampling interval. Based on the input received from work-study officers, it was decided that five samples drawing on an hourly basis³¹ was optimal.

The \bar{x} and R chart was the most appropriate control chart type to test the stability of the production process (for the quality characteristic back-coverage), given the subgroup size (see Swift, 1995, p. 208 for a flow chart on control chart selection). Nelson (1984) prescribes 8 possible tests for detecting special cause variation from \bar{x}

³¹ The sampling frequency can also be determined based on the average run length (Karlsson & Åhlström). For details see Wadsworth, Stephens, and Godfrey (2002).

and R chart although the first four (according to Nelson) tests are the most important. These four tests for special cause variation (Table 5.7) were used in this study to test for presence or absence of special cause variation.

Table 5.7: The Control Chart Tests Used in the Study (adopted from Nelson, 1984)

Test #	Indication of a Potential Special Cause Variation
1	One point more than 3 standard deviations from centre line
2	Nine points in a row on same side of centre line
3	Six points in a row, all increasing or all decreasing
4	Fourteen points in a row, alternating up and down

5.5. DESIGNING AND CONDUCTING THE OPTIMISATION EXPERIMENT

5.5.1. Identifying the Experimental Factors and Their Levels

As mentioned in section 5.3.4, brainstorming led the researcher and the team to identify three control factors: Stitch density (stitch density is measured in stitches per inch (SPI)) adjuster screw length, Presser foot pressure, and Feed-dog height. The brainstorming also led the researcher and the team to identify three noise factors: Fabric type, Presser foot condition, and Handling techniques. In the next step, the levels for these six key factors were identified so as to fit them into an appropriate orthogonal array. Based on the information gained during brainstorming the researcher guessed that there would not be much of a curvature in the response surface (it was decided that the quantitative factors would not be manipulated over a very wide range, even if it was practically possible) and hence manipulating the factors at two-levels would suffice. A description of all six factors and the levels identified for each factor are described as follows.

Fabric is received by the factory in batches with variations within and between batches based on colour, weight etc. from the supplier for the same style. Thus, in this experiment, for the first noise factor, two types of fabric (both consisting of 91% cotton, 9% spandex) were considered based on their weight: 162 g/m² (level 1, coded as -1

based on the conventional notation) and 165 g/m² (level 2, coded as +1 based on the conventional notation) (Table 5.8).³²

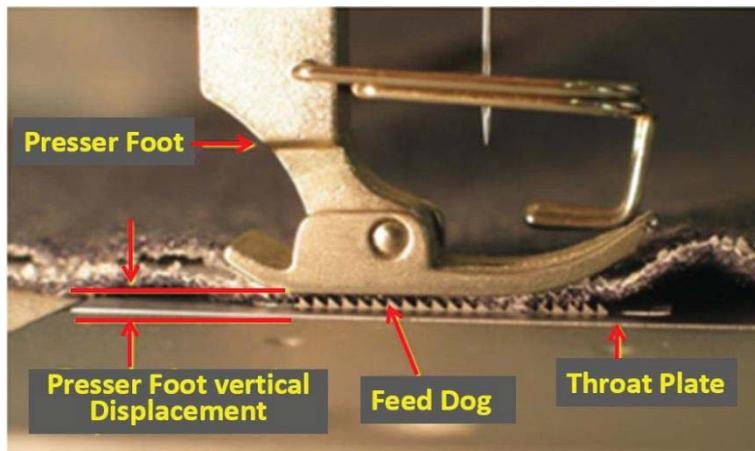


Figure 5.14a: Experimental factors (source: Carvalho et al., 2012)

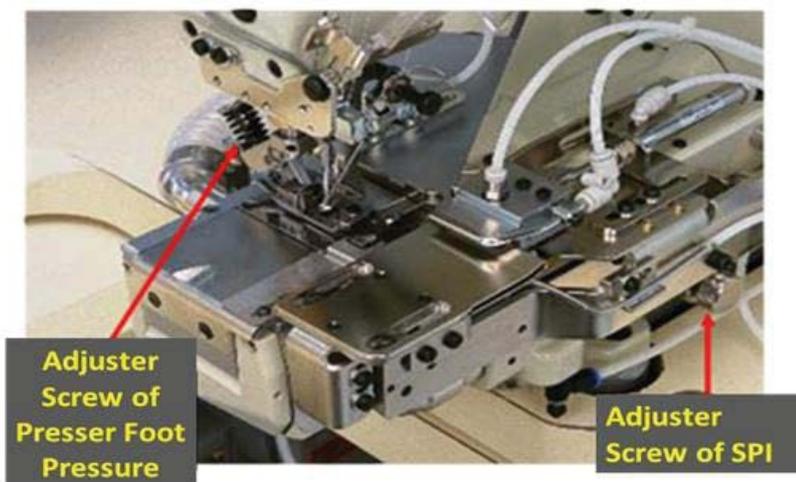


Figure 5.14b: Experimental factors

The handling technique, the second noise factor that accounts for the variation of the back-coverage measurement (its effect depends on the operator experience) was simulated by choosing two operators having dissimilar sewing experience. Level 2 (+1) represented an operator having 6 years of experience in sewing Thongs while level 1 (-1) represented an operator who has been having only a few weeks of experience in sewing Thongs.

³² Perhaps weight of the fabric is not a good proxy to distinguish between the two fabrics. It is important to note that there is a significant difference between the 162 g/m² fabric and the 165 g/m² fabric in terms of handling. The former is more difficult to handle than the latter.

The third noise factor (Presser foot condition) represents the fact that garments are sewed using sewing machines that have pressure foots of varying age (some being brand new while some being in use for long time). The age/condition of the pressure foot is thought to cause variability in one or more of the three quality characteristics (Table 5.6). The brainstorming revealed that a worn presser foot tends to cause problems in feeding the garment, which in turn tend to transmit some variation to the quality characteristics of the garment (e.g. back-coverage measurement). Instead of replacing pressure foot, the mechanics in the factory fix a Teflon cladding to presser foots after they are being used for some time, in order to recondition them to act as new pressure foots. To simulate the noise caused by the presser foot condition, an old presser foot with a Teflon cladding was assigned to level 1 (-1) and a new presser foot was assigned to level 2 (+1).

The brainstorming also revealed that the presser foot pressure is an important control factor. The presser foot (the first control factor) provides the required pressure to control fabric feeding. The height of the presser foot spring was considered as a reliable proxy for presser foot pressure. The height of the pressure foot spring (presser foot pressure) was set at 21 mm to represent level 1 (-1) while the height was set at 22 mm to represent level 2 (+1) in the experiment.

Feed-dog, a teathed element in the sewing machine that supports feeding the fabric in conjunction with the presser foot, was the second control factor. In sewing, the height of the feed-dog is set based on the characteristics of the fabric (elasticity, thickness etc.) and a calibrated scale ranging from 1 to 5 is available in the machine to adjust the feed-dog height. Height of the feed dog set at level 1 in the calibrated scale was treated as level 1 (-1) while the height set at level 4 in the calibrated scale was treated as level 2 (+1) in the experiment.

The final experimental factor, Stitch density, refers to SPI used in sewing. SPI can be adjusted by changing the length of the SPI adjustment screw available in the over-lock sewing machine. While SPI can be adjusted with the screw, the brainstorming revealed that the actual SPI count in a sewed garment does vary from one place to another, depending on noise factors such as the handling technique, fabric type, and the sewing speed. Table 5.8 depicts the levels of all six factors used in the experiment.

Table 5.8: Factors and Levels Used in the Experiment

Factor Description	Label	Level 1 (-1)	Level 2 (+1)
SPI adjuster screw length	A	20.5 mm	21 mm
Presser foot pressure	B	21 mm	22 mm
Feed-dog height	C	1	4
Fabric type	D	Low g/m ²	High g/m ²
Presser foot condition	E	Old (reconditioned)	New
Handling techniques	F	Low Experience	High Experience

5.5.2. The Design Matrix and Response Data

In this experiment, crossed-arrays were setup using an L8 orthogonal array for the inner array (three control factors were assigned to the inner array) and another L8 orthogonal array for the outer array (three noise factors were assigned to the outer array) to obtain the data, as shown in Table 5.9 (see Roy, 2010, p. 211-229 for different orthogonal arrays prescribed by Genichi Taguchi) The QI team members were also taught how to select an appropriate array (e.g. L4, L8, L9, L12 etc.) from a list of standardised arrays available, given the number of factors in the experiment.

The two levels of each factor are represented by a ‘-1’ and a ‘+1’ in the matrix.

Table 5.9: The Orthogonal Array Used for Conducting the Experiment

Control Factors			Noise Factors									
A	B	C	D	-1	-1	+1	-1	+1	-1	+1	+1	L8
			E	+1	-1	-1	-1	-1	+1	+1	+1	
			F	+1	+1	+1	-1	-1	-1	+1	-1	
-1	-1	-1	<i>Response Data</i>									
-1	-1	+1										
-1	+1	-1										
-1	+1	+1										
+1	-1	-1										
+1	-1	+1										
+1	+1	-1										
+1	+1	+1										

The control and noise factors were then manipulated in a random order as per the design matrix/orthogonal array, and the values of the response measurements were recorded in three data recording sheets (one for each response variable) in the space allocated for recording response data (see Table 5.9). The results and discussion associated with the experiment, which include the assessment of two data analysis methods (Taguchi methods and conventional DoE methods), are covered in Chapter 7. The reader should note that the researcher conducted a confirmation experimental run (results in section 7.3.1.1) to confirm/validate the optimum parameter settings produced by the statistical analysis.

The researcher explained to the quality improvement team that the logic of the experiment is based on the hypothesis that there exists an optimum machine setting that results in the least amount of difficult sewing manoeuvres (hence less variability of the response variables such as the back-coverage) to overcome different types of fabric, machine conditions (presser foot conditions), and handling conditions.

5.5.3. The Forerunner Experiment

The main experiment described in the preceding section is a full scale experiment (resource intensive). However, it is designed to be conducted in a work environment which is not familiar with the RPD methodology. This was envisaged by the researcher at the very outset. The researcher deemed conducting a full scale experiment upfront somewhat risky (and perhaps unethical), even though the management had no objection to it. Therefore, a small scale experiment was conducted beforehand (this experiment is referred to as the forerunner experiment in this thesis) to introduce the RPD methodology to the quality improvement team. The statistical objectives of the experiment were to: (a) identify possible two-way interactions, (b) identify how hard it is to change the factors, (c) estimate the time taken to change each control and noise factor settings, and (d) understand the behaviour/response (e.g. fatigue, ability to follow instructions such as changing the operator and other factor levels depending on run pattern shown in the design matrix/orthogonal array) of sewing operators and support staff (the mechanics who need to change some factor settings) while conducting the experiment.

To reiterate, the forerunner experiment was conducted mainly to reduce the risk of failure of a full scale RPD experiment by establishing that the RPD approach has the potential to provide useful outcomes for the factory. In addition, staff buy-in and training the researcher and other participants (sewing operators, mechanics, and the quality controller) for the main experiment were the secondary objectives of the forerunner experiment. It can also be argued that conducting two experiments is better than conducting one experiment because two experiments give more data and more opportunities for researcher-respondent interactions. The details of the forerunner experiment (including results and the discussion) are given in Appendix D.

5.6. QUALITATIVE RESEARCH METHODS

Qualitative research differs from quantitative research in that the data collected in qualitative research are primarily of textual in nature—that is, words as opposed to being numbers (Bryman, 2012; Cooper & Schindler, 2014). In addition, a qualitative study is typically inductive in nature (theory formulation) as opposed to being deductive (theory/hypothesis testing) in nature (Bryman, 2012). In the next section, the researcher describes how she collected and used nonnumeric (textual) information to develop a model (theory) to explain the organisational change management dynamics when Taguchi’s RPD approach is being integrated in a Lean manufacturing environment to improve *design quality*. The objective of this section is to examine key qualitative research methods available, in order to select the most appropriate method to meet the research objective—more specifically, objective # 3 (to identify and describe the drivers and restraints associated with attempting to integrate Taguchi’s RPD approach in a mature Lean organisation in apparel manufacturing).

Bryman (2012) identifies five main qualitative methods: *Ethnography/participant observation*, *Qualitative interviewing*, *Focus groups*, *Language-based approaches*, and *Secondary analysis* (collection and analysis of available texts and documents). Possible methods that could be used in the study are described in turn.

5.6.1. Ethnography/Participant Observation

Ethnography is a “systematic study of people and culture” to explore “cultural phenomena” (Bryman, 2012; Yin, 2011). Creswell and Miller (2000) observe several

salient features in ethnography: observing groups of people in a natural setting, conducting interviews to clarify the ethnographer's observations, immersing thoroughly in the social setting (to the point that the ethnographer becomes a learner), low or no knowledge about the phenomena being studied prior to engagement (observing the participants) in the social context, and long or prolonged involvement in data collection (e.g. making observations, verifying facts, and taking field notes); for these reasons, it is typical for an ethnographer to spend 4 to 12 months in the field to collect meaningful data (Creswell & Miller, 2000).

Ethnographic approaches are justified in organisational research if the aim of the researcher is to either understand the role of a certain organisation (e.g. role of a correction facility for juvenile delinquents), or to explain certain practices/behaviours (e.g. explaining why organisational members in a certain setting may resist a productivity improvement initiative), or to examine social interactions (Hammersley & Atkinson, 2007; Willis & Trondman, 2000).

Ethnographers adopt an open mind about the cultures of the subjective field; they beginning their investigation with a problem and a theory (or a model) to be addressed. Typically, an ethnographer would formulate certain initial questions as a guide to make observations, and thereby collect data (Willis & Trondman, 2000). Like in any other research design, access to data (in the target population of interest) is a critical success factor in ethnography. In certain settings the researcher may have an open access (free access) to the target population (e.g. a public event) while in other settings the access may be restricted (closed), in which case, the permission needs to be sought from the relevant authority to gain access to the target population (Brewer, 2000).

Richardson (2000) prescribes five criteria to evaluate ethnography³³: substantive contribution, aesthetic merit, reflexivity, impact, and expression of a reality. According to Richardson, substantive contribution refers to the study being able to substantively contribute towards understanding the social phenomenon being studied; aesthetic merit refers to adaptation of "creative analytical practices" such as using aesthetically pleasing yet nontrivial constructions to narrate the responses; reflexivity refers to describing how well the ethnographer executed the process (e.g. the study being

³³ It is important to note that the term ethnography is used to refer to the method as well as the write-up (reporting of the study) (Bryman, 2012). In this instance, the researcher means the latter.

seemingly unbiased, addressing ethical issues and describing sufficiently how the information was gathered); impact refers to extent to which the study impacts the reader both intellectually and emotionally; finally, expression on reality refers to extent to which the study appears to be true/real, in the eyes and mind of the reader.

Although in the ideal world an ethnographic study should be free from observer biases, in the real-world it may be difficult for an ethnographic study to become so because by nature, ethnography requires the researcher to immerse himself/herself in the social setting being investigated (Bryman, 2012; Fetterman, 2010; Willis & Trondman, 2000). For this reason ethnographers often use triangulation approaches, contextualisation, and non-judgmental orientation to negate any negative influence that may result from ethnographic engagement with the participants (Fetterman, 2010). Divale (1976) asserts that the ethnographer's familiarity with the values/culture of the participants (e.g. the ethnographer being able to communicate freely in the native language of the participants) does enhance the validity and reliability of data being collected. .

Unlike the other qualitative methods (details follow), ethnographic approach offers a distinct advantage to the researcher in achieving the objectives (more precisely objective 3) of the study. This is because both the researcher and the participants had very little (if any) prior knowledge on the drivers and restraints that govern organisational change towards integrating Taguchi's RPD approach into the Lean culture. This is mainly because .the participants have had no experience on Taguchi's RPD approach up until the researcher introduced this approach to the participants (the case study factory). Alternative qualitative methods such as qualitative interviews/surveys and focus groups do not suit the study because metaphorically speaking, there is nothing to interview or focus if the respondents have not been exposed to Taguchi's RPD approach! In addition, organisational change is a cultural phenomenon which is best addressed by ethnography.

5.6.2. Qualitative Interviewing

Qualitative interviewing is a broad term that is used to refer to any form of interviewing that prompt the respondents to provide textual information (e.g. requesting a respondent to select one of the 5 options given by the researcher). Thus all forms of structured, unstructured and semi-structured interviews that result in the generation of textual

information (as opposed to numeric information) can be classified under qualitative interviewing (Bryman, 2012; Fontana & Frey, 2000). The ultimate objective of qualitative interviewing is to gather rich in-depth information on participant's experience on a particular phenomenon or on participant's knowledge on a particular topic (Myers & Newman, 2007; Turner, 2010). Turner observes that a well-designed interview protocol—a set of high-level questions that the researcher needs to address in conducting the interview— is one of the most important quality requirements in qualitative interviewing. Bryman (2012) observes that qualitative interviewing can be part of an ethnographic research process.

5.6.3. Focus Groups

Focus group approach involves interviewing more than one person simultaneously, in a group setting under the direction of a moderator/facilitator (Bryman, 2012; Gaskell, 2000).³⁴ In a broad sense, focus group method can be considered when information cannot be gathered very efficiently from other qualitative methods (Bryman, 2012; Gaskell, 2000).

5.6.4. Secondary Analysis of Textual Data

Textual data/information relevant to a study can sometimes originate from secondary sources (Bryman, 2012). For example, a researcher can gain a reasonable understanding about the culture of an organisation by analysing the text used in official communication (e.g. letters, memos). Such textual information can often be used as additional data to triangulate the findings generated from primary qualitative data collection mechanisms such as ethnography and qualitative interviewing (Bryman, 2012).

³⁴ Typically the researcher also becomes the moderator (Bryman, 2012; Frey & Fontana, 1991).

5.7. THE METHODOLOGY ADOPTED TO UNDERSTAND THE DRIVERS AND RESTRAINTS OF USING TAGUCHI'S RPD APPROACH

As evidenced in Figure 5.7 the third wave of data collection was run almost in parallel with second wave of data collection. While the second wave of data collection related to collection of quantitative data before and during the RPD experiments to understand and analyse variability, the third wave of data collection primarily related to collecting qualitative data³⁵ to understand what drives and what inhibits the movement from the current organisational state of not using the RPD approach, to the desired state of using this approach as the tool of choice to make products (or processes) less sensitive to environmental noise—that is, reducing the variability of the product's quality characteristic (functional characteristic) due to environmental noise. As mentioned earlier, the qualitative data required in the third wave of data collection were collected whilst interacting with the staff to conduct the RPD experiments and other studies that preceded the experiments. This was why the two streams of data collection ran in parallel. The researcher used the Kurt Lewin's force field theory (Lewin, 1951; Schein, 1996) on organisational change as the theoretical framework to which the third wave of data collection relates to.

5.7.1. Lewin's Force Field Theory

The origins of Lewin's forced field theory (Lewin, 1951) can be traced back to the pioneering research (starting in the 1920s) done by Kurt Lewin to develop his "field theory" in psychology (Burnes & Cooke, 2013). In psychology, a field theory can be viewed as a model (theory) that explains (and predicts) individual behaviour as a function of the self (the individual) and the field (the environment) (Burnes & Cooke, 2013; Schein, 1996). In an organisational context, Force Field Analysis can be used to understand the group dynamics associated with a planned change. It is not the intention of the researcher to review force field theory as a theory on applied psychology or organisational behaviour; in this thesis the researcher reviews force field theory from a practical perspective, as a tool used in quality and operations management (e.g.

³⁵ Qualitative data were also used identify the merits and demerits of Taguchi's RPD approach, in connection with the third research question.

Brassard & Ritter, 2010; Maslen & Platts, 1994; Pyzdek, 2003) to implement a planned organisational change.

Lewin's force field theory assumes that an organisation will be at a state of "quasi-equilibrium" (prior to a change), governed by the combined action of driving forces and restraining forces, which prevents the organisation from moving from its current state to the desired state (Thomas, 1985). Driving forces are the forces that drive the change while the restraining forces are the forces that inhibit (restrain) the change (Thomas, 1985). Lewin's force field theory posits that a successful organisational change goes through three steps: unfreezing, moving to the new level, and refreezing (Lewin, 1963). Figure 5.15 depicts a generic force field model that depicts the state of moving (the second step of organisational change) towards the desired organisational change. The role of the change agent³⁶, according to Lewin's force field theory, is to unfreeze the existing organisational state to enable the organisation to move (progress through the transition state) towards the desired organisational state (Figure 5.15) and then "refreeze" to stabilise the transition (Lewin, 1963, p. 228). Note that unequal lengths of the arrows (the longer the arrow, greater the force) shown in Figure 5.15 depict unequal strengths of forces that prevail at a given situation.

³⁶ The researcher does not profess to be a change agent. Effecting the actual organisational change (if at all possible) is a practical matter; besides proving specific advice to the factory management is a matter that is beyond the scope of this academic research.

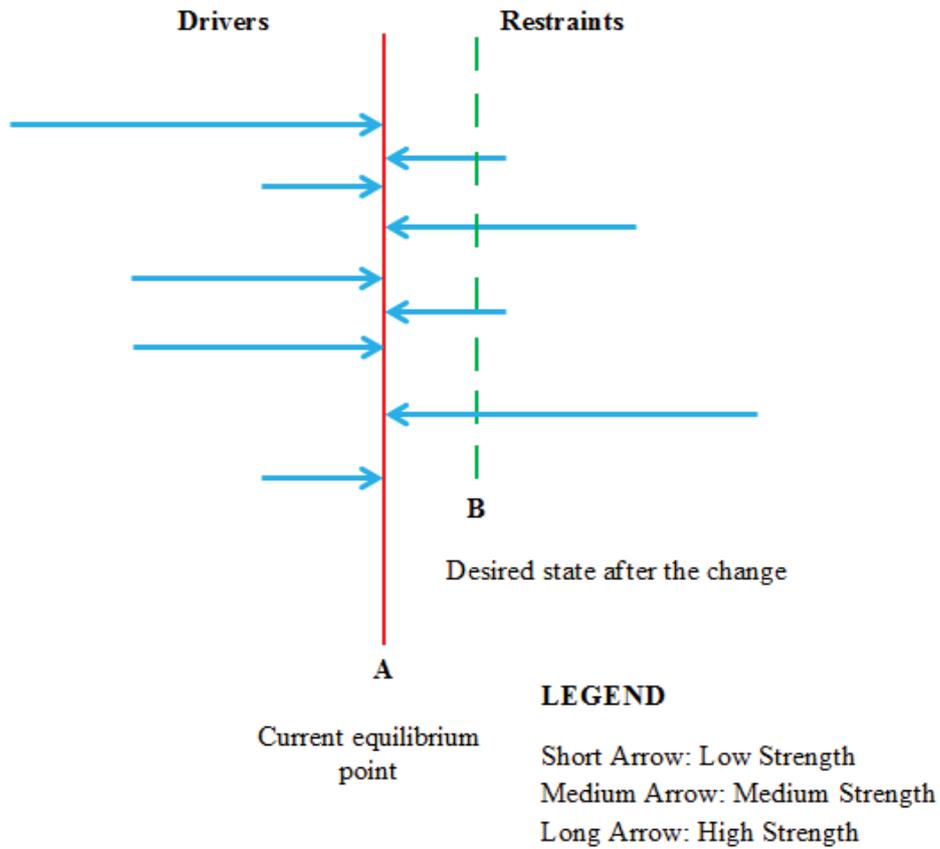


Figure 5.15: A generic force field model at the state of moving (adopted from Thomas, 1985)

Thomas (1985) advocates that the preferred approach of unfreezing and moving towards the desired state is to reduce the restraining forces rather than increasing the driving forces, because increasing driving forces (without reducing the restraining forces) tend to increase organisational conflict.

The specific aims of the third wave of data collection were as follows:

- To identify the drivers and restraints that prevail in the Lean environment, should the Lean organisation decide to implement Taguchi's RPD approach as the default approach to make products (and/or processes) less sensitive to environmental noise.
- To assess the relative strengths of each driver and restraint identified.
- To identify the organisational (factory) climate (culture) in order to propose (in a non-prescriptive way) how the organisation could unfreeze and move

towards the desired state. The desired state being adopting Taguchi's RPD approach by default to make products (and/or processes) less sensitive to environmental noise.

5.7.2. Specific Data Collection Methods Used by the Researcher

5.7.2.1. Participant Observations

The researcher spent nearly six months (Figure 5.7) in the case study factory, actively engaging with the staff. In the process, as mentioned earlier, she earned the trust of her participants (Table 5.4); this facilitated the collection of information required for her to answer her third and fourth research questions—in particular, the latter. Answering the fourth research question required identifying the drivers and restraints that govern the desired organisational change in making Taguchi's RPD approach as the method of choice to solve variation problems concerning robustness. Participant observations (ethnographic engagements) also enabled the researcher to assess the strength of each driver and restraint using a 3-point scale (low/medium/strong) as part of her Force Field Analysis.

The reader will note from Table 5.4 that the researcher has used multiple sources (where possible) to collect essentially the same data (e.g. the researcher interviewed the general manager, plant manager, quality manager, and the operators to understand variation problems and how these are currently been handled). This type of cross validation and triangulation is deemed necessary in participant observations to increase the reliability and validity of qualitative data (Barratt et al., 2011; Johnson, 1997; Morse et al., 2008; Voss et al., 2002). The researcher also has had an opportunity to participate in a few workshops and training programmes meant for the employees. These opportunities were also good openings for the researcher to become a participant observer. The sources of data collection within the case study are described as follows.

5.7.2.2. Interviews

The researcher choose the ethnographic interview approach; she had, what could be described as “ethnographic engagements”, with a number of managers at all levels of the case study factory to understand its climate/culture (the way in which work is

organised and done in the factory) and problem solving approaches; the researcher also cross-validated the information provided by her informants (i.e. managers) by actually engaging herself with the frontline works; secondary data (see the next subsection) were also used to cross-validate the information provided by the informants. The researcher also engaged with the managers and operators to test their reactions to RPD approaches before, during, and after conducting the RPD experiments.

5.7.2.3. Secondary Data

Most of the data collected for the study were primary data, that is, data collected by the researcher using her measurement/observation methods. The primary data include quantitative data collected during the first wave of data collection using the survey questionnaire (details in Chapter 4), quantitative data collected by the researcher during the second wave of data collection (data generated from the RPD experiments and other preceding studies such as the Gauge R&R study, process stability analysis, and process capability analysis), and last but not the least, qualitative data collected by the researcher using participant observation and interviews (ethnographic engagements). However, secondary data were also used by the researcher to enrich the findings. The researcher used a number of sources belonging to the case study factory such as company records on the application of Continuous Improvement tools (e.g. the cause-and-effect diagrams, records on the 5 Whys analysis), company forms, and visual charts such as performance charts, to support and cross-validate her primary data collected in the third wave of data collection.

5.8. CHAPTER CONCLUSION

This chapter described the methodology used to answer the third and fourth research questions. The third research question relates to assessing RPD experimental methods (Taguchi methods and the response surface alternative as a reference point to compare Taguchi methods against) as a problem solving tool to reduce variation problems (caused by uncontrollable environmental factors) in a Lean manufacturing environment in apparel production. The fourth research question relates to understanding the forces that drive or restraint the organisation towards using Taguchi methods as the tool of choice to solve variation problems.

The chapter began by introducing the case study method as well as the factory (in particular the Lean operating system in the factory) that was used to collect the data. A substantial part of the chapter was dedicated to explaining the sequence of steps that were followed before and during the RPD experiments that were designed to reduce the variability of a particular style of an upmarket women's garment (a Thong); the variability being thought to have been caused mainly due to three uncontrollable environmental factors: handling (operator to operator variations), fabric (variations in the fabric type used) and the presser foot condition of the sewing machines (the root cause analysis used to identify the factors are covered in section 5.3.4). The remaining part of the chapter was dedicated to explaining how the author went about in identifying the drivers and restraints that govern the desired organisational change of using RPD as the default method to solve variation problems that arise due to noise caused by the uncontrollable factors. Lewin's force field theory (Lewin, 1951) was the theoretical framework used by the researcher to identify the drivers and restraints as well as their relative effects on organisational change. The data collection methods related to Force Field Analysis was covered in this chapter (section 5.7).

An important feature in the researcher's methodology is "triangulation". The triangulation approach is adopted in social research to study the same phenomenon using different methods and different data to get a richer perspective of what is being studied and what is being uncovered—the objective being to increase the validity of the study (Cox & Hassard, 2005; Wang & Duffy, 2009). The researcher used the post-positivism triangulation approach. More specifically, she used the *between method triangulation* approach where different methods are used on the same object (Cox & Hassard, 2005; Wang & Duffy, 2009).

The next chapter covers the test results on researcher's theoretical model (the model development was covered in Chapter 4) and the implications of the results from a practical perspective. As mentioned in Chapter 4, the researcher's theoretical model was tested based on data collected from 318 respondents (working in 31 factories belong to the Lean manufacturing organisation) through the questionnaire developed by the researcher (the details of the questionnaire development are given in Chapter 4).

CHAPTER 6

FINDINGS ON EMPIRICAL MODEL TESTING AND IMPLICATIONS

“Statistics is the grammar of science”

—Karl Pearson

6.1. INTRODUCTION

Chapter 6 focuses on achieving the first research objective by way of answering to the first two research questions through empirical model testing. The development of the empirical model (Figure 4.1) as well as the survey instrument that used to collect data to test the model was covered in Chapter 4.

Section 6.2 provides an overview on Structural Equation Modelling (SEM), the generic statistical approach used in testing empirical models involving latent variables (constructs). Three subsections are included under this section. The first two subsections cover the two SEM methods used in the literature: the covariance based SEM approach (section 6.2.1) and the partial least squares based SEM approach (section 6.2.2). Having reviewed both approaches, the researcher justifies that the covariance approach is the more suitable approach for testing the proposed theoretical model. The third subsection (section 6.2.3) covers a technique known as “item parcelling”, a technique used in the covariance approach to resolve large number of measures to a fewer numbers of measures, when a large number of measures are involved in representing latent variables (constructs).

Section 6.3 presents the descriptive statistics of the survey data. Section 6.4 provides the test results on the validity of the constructs. This section is subdivided into six subsections. Section 6.4.1 provides evidence of absence of any “method bias” (Podsakoff & Organ, 1986) in the administration of the survey. Section 6.4.2 shows evidence of unidimensionality of the constructs. Section 6.4.3 shows how certain measures were parcelled to reduce the number of measures for each construct. Section 6.4.4 shows evidence of the reliability of the measurement scales used for each construct. In essence these four subsections cover the prerequisites for “construct

validity” (Nunnally & Bernstein, 1994). Sections 6.4.5 and 6.4.6 show direct evidence of “construct validity”, through factorial validity (section 6.4.5) and convergent and discriminant validities (section 6.4.6).

Section 6.5 provides the test results on the research hypotheses and an accompanying discussion on the interpretation of results from a theoretical and practical perspective. Finally, section 6.6 provides the key findings of the chapter (the chapter conclusion).

6.2. STRUCTURAL EQUATION MODELLING

Structural Equation Modelling (SEM) is a statistical technique used mainly by social, behavioural, and educational scientists to model and test structural relationships involving directly unobservable variables (also called latent variables, factors, or constructs), using a measurement system involving directly observable variables (also called manifest variables or measures) (Byrne, 2010; Raykov & Marcoulides, 2006). The factor analytic approach used in SEM is confirmatory rather than exploratory; the goal is to confirm the hypothesised relationships between the factors (latent variables/constructs/concepts) as well as the relationships between the factors and their underlying measures (Byrne, 2010). The SEM techniques provide explicit estimate of the measurement error associated with individual measures, which is not the case if these measures were regressed using traditional multivariate procedures such as multiple regression (Byrne, 2010; Raykov & Marcoulides, 2006). As such SEM methods (particularly the covariance based approach covered in the next section) provide more precise estimates on the strengths of hypothesised relationships between the latent variables (constructs) (Chin, 1998; Fornell & Larcker, 1981).

The generic assumption that holds across all forms of SEM is that the relationships between the variables are linear. That is the hypothesised relationships between the constructs as well as the relationship each construct has with its underlying measures are linear. The other assumptions depend on which of the two SEM approaches/techniques being used: the covariance based SEM (CBSEM) and the partial least squares based SEM (PLSBSEM). These two SEM techniques are described in the next two subsections.

6.2.1. The Covariance Based SEM Approach

The CBSEM approach/technique, which is also known as Linear Structural RELations (LISREL), was developed by Karl G. Jöreskog (Jöreskog, 1970) as a general method of analysing the covariance structure of measures that underline latent variables (constructs). Due to certain superior benefits over the PLSBSEM technique (details given later), the CBSEM technique is often the technique of choice for testing theoretical models involving latent variables and their accompanying measurement systems (Chin, 1998; Grigg & Jayamaha, 2014; Shah & Goldstein, 2006). The researcher observes that the term CBSEM is synonymous with SEM in psychometrics rich disciplines (see Iacobucci, 2010; McDonald, 1996) and also, sometimes even in operations management (see Peng & Lai, 2012; Shah & Goldstein, 2006).

Since the researcher used the CBSEM technique to test her theoretical model (including testing the validity of the constructs in the model), a basic description of this technique, along with specific terminology used, is provided as follows (the researcher uses her theoretical model for ease of explanation).

Figure 6.1 depicts the researcher's hypothesised relationships between the constructs (see the thick red lines) along with the relationships each construct has with its underlying measures (the rationale of selecting the 15 measures V1 through to V15 is described later).

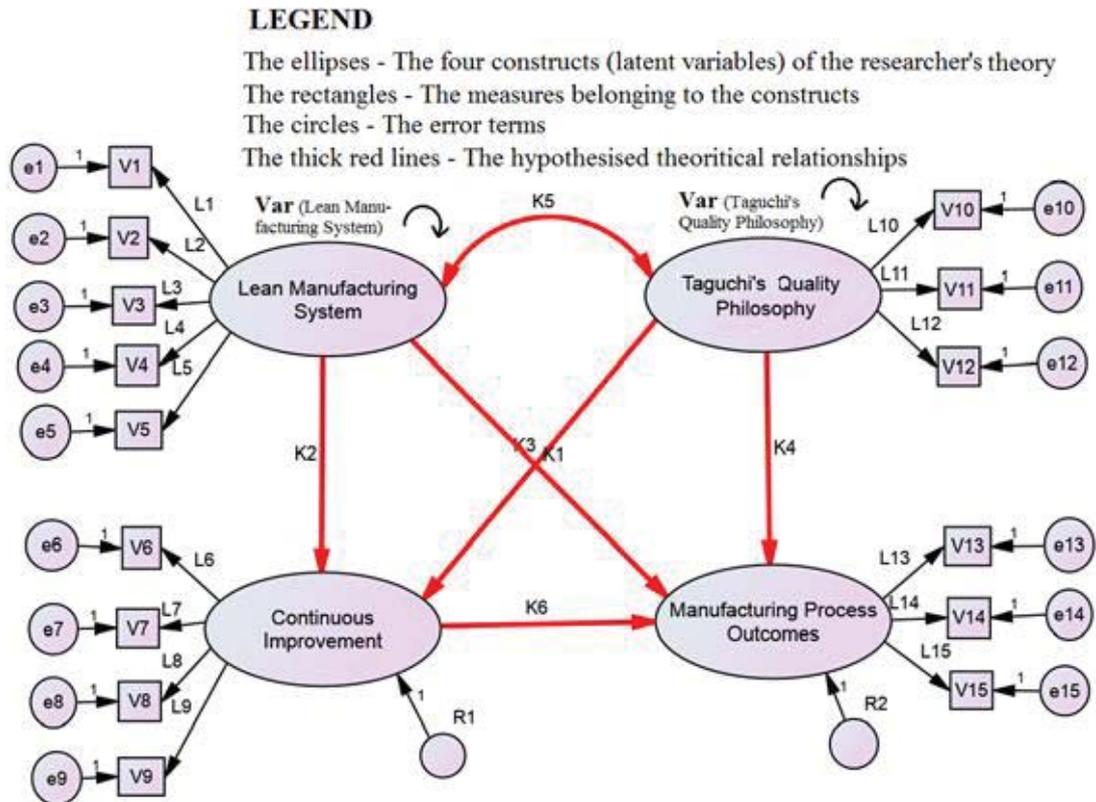


Figure 6.1: The parameterisation of the researcher's theoretical model in CBSEM

There are always two kinds of constructs in any model that involves CBSEM: exogenous constructs and endogenous constructs. An exogenous construct is a construct for which variability is not explained by any predictor construct/s (Byrne, 2010); in the researcher's model (Figure 6.1), the two exogenous constructs are Lean Manufacturing System and Taguchi's Quality Philosophy. The variances of exogenous constructs (abbreviated as Var in Figure 6.1) remain unknown parameters to be estimated, alongside other unknown parameters (Byrne, 2010; Kline, 2011). An endogenous construct is a construct for which variability is explained by its predictor construct/s (Byrne, 2010); in the researcher's model (Figure 6.1), the two endogenous constructs are Continuous Improvement (CI) and Manufacturing Process Outcomes.

The CBSEM involves two types of linear structural relationships: *the relationships each construct has with its measures* (e.g. $V1 = L1 \times \text{Lean Manufacturing System} + e1, \dots V5 = L5 \times \text{Lean Manufacturing System} + e5$) and *the predictor-response relationships involving the endogenous constructs* (e.g. $\text{Manufacturing Process Outcomes} = K3 \times \text{Lean Manufacturing System} + K4 \times \text{Taguchi's Quality Philosophy} + K6 \times \text{CI} + R2$).

In the researcher's model there are 40 unknown parameters to be estimated: 2 variances involving the exogenous constructs, 15 factor loadings (L1 through to L15), 15 measurement error variances involving the 15 measures (Var e1 through to Var e15), 2 residual error variances (Var R1 and Var R2) involving the two endogenous constructs and six structural regression coefficients (K1 to K6) corresponding to the researcher's six research hypotheses.

An important covariance matrix that the CBSEM algorithm computes is the so-called *implied covariance matrix* involving the measures; each element in this covariance matrix is expressed as a function of the unknown parameters³⁷ using the specified linear structural relationships (Kline, 2011). The CBSEM algorithm estimates the values of the unknown parameters in an iterative fashion such that the discrepancy between the implied covariance matrix of the measures and the observed covariance matrix of the measures becomes minimal (Bollen, 1989; Mulaik, 2009).³⁸ A model is said to be a "perfect fit" to data (in a covariance sense) if the aforesaid discrepancy could only be attributed to the sampling error (Bollen, 1989; Kline, 2011; Mulaik, 2009). A model is said to be a "good fit" to data (or an "acceptable fit" to data) if the discrepancy is below the respective cut-off values (for a good fit and an acceptable fit) expressed via a raft of goodness of fit measures (Bollen, 1989; Kline, 2011; Mulaik, 2009).

One of the main advantages in CBSEM over PLSBSEM is that CBSEM is a "full information" approach in that all unknown model parameters are estimated simultaneously using a global optimising procedure (as mentioned above, this procedure minimises the discrepancy between the implied covariance matrix and the observed covariance matrix). Another important advantage in CBSEM (over PLSBSEM) is the high accuracy of the estimated structural regression coefficients (hence better interpretation of test results of research hypotheses), as long as a sufficiently large sample size is chosen to estimate the covariances (Bollen, 1989; Kline, 2011; Mulaik, 2009). However, CBSEM is reliant on the usual parametric assumptions: normally distributed data³⁹ and independence of observations. In addition, the CBSEM method

³⁷ In the researcher's model (Figure 6.1), since there are 15 measures, there would be 15 diagonal elements and 105 non-diagonal elements (being $15 \times (15-1)/2$) in the implied covariance matrix as well as in the observed covariance matrix; the 120 covariances in the implied covariance matrix will be estimated by varying the values of the 40 unknown parameters iteratively.

³⁸ Typically the maximum likelihood discrepancy function prescribed by Jöreskog (1970) is used.

³⁹ More precisely, *multivariate* normally distributed data (data means the scores of the measures).

assumes that all error terms (e.g. e1 to e15 plus R1 and R2 in Figure 6.1) are uncorrelated (Bollen, 1989; Kline, 2011).

6.2.2. The Partial Least Squares Based SEM Approach

Partial Least Squares Based SEM (PLSBSEM) approach is a nonparametric approach proposed by Herman Wold (Wold, 1982), the mentor of Karl G. Jöreskog, as an alternative to CBSEM. The PLSBSEM method proceeds from the premise that even though the constructs of a model are latent, it is possible to compute the scores of these latent variables as weighted linear combinations of their underlying measures—the greater the number of measures, the more accurate the estimates of structural regression coefficients become (Chin, 1998; Tenenhaus, Amato, & Esposito, 2004). Thus in PLSBSEM, for accurate estimates (consistency) of the strengths of hypothesised relationships, not only large samples are required⁴⁰ but also a large number of measures are also required for each construct; this property in PLSBSEM is known as “consistency at large” (Grigg & Jayamaha, 2014; Haenlein & Kaplan, 2004).

PLSBSEM involves a series of locally optimised (i.e. partially optimised) least squares regression models. As such, unlike in CBSEM, there is no overall goodness of fit measure (i.e. a global goodness of fit measure) in PLSBSEM to examine to what extent a researcher’s theoretical model (including the measurement system used by the researcher) fits the observed data (Chin, 1998; Tenenhaus et al., 2004). For this reason, the PLSBSEM approach is sometimes referred to as a “limited information” approach (Grigg & Jayamaha, 2014). This disadvantage notwithstanding, PLSBSEM is chosen as the appropriate SEM method when a researcher encounters one of the following situations: (a) having to deal with concepts (constructs) whose meaning evolves swiftly

⁴⁰ The precision of model parameters (regression coefficients) in the partial least squares method depends not only on the number of observations (cases) but also on the number of indicators one includes under each construct (more indicators one uses the better). It is not possible to determine the theoretically minimum number of indicators one should use. However, assuming that one has used sufficient number of indicators to cover the conceptual domain of a construct, determining the sample size becomes a basic power analysis exercise in regression (for details, see Cohen, 1992). In the case of researcher’s model (Figure 6.4), Manufacturing Process Outcomes is being predicted by 3 predictors. Thus, according to Cohen’s power analysis calculations, if an analyst envisages a strong relationship between Manufacturing Process Outcomes and its 3 predictors, the minimum sample the analyst requires is 76 cases, at 5% significance level (Cohen, 1992, p. 158). Cohen defines a strong relationship to mean a “large effect”, for which, he has given the arbitrary condition $R^2 \geq 0.26$, based on the parameter Cohen’s $f^2 (= 0.35)$, which is equal to $R^2/(1-R^2)$.

over time (e.g. concepts in information science), (b) having data that do not meet the parametric assumptions, (c) having “formative constructs” in the model, (d) when theory testing is not the central focus of a study, (Chin, 1998; Grigg & Jayamaha, 2014; Tenenhaus et al., 2004).⁴¹

The four constructs in researcher’s theoretical model represent well-defined concepts (Taguchi’s Quality Philosophy is the only construct that can only be treated as a construct that is new). Researcher’s data met the parametric assumptions of normality and independence and there were no formative constructs in the model. Moreover, theory testing is indeed the central focus in the first research objective of the study. Therefore the researcher discarded the PLSBSEM approach in favour of the CBSEM approach. In the next section, the researcher describes a technical strategy (known as measurement item parcelling) frequently used in CBSEM when a large number of measures are used to operationalise a construct.

6.2.3. Measurement Item Parcelling in CBSEM

Unlike in PLSBSEM, statistically speaking, a large number of measures are not required to operationalise a construct in CBSEM (Bollen, 1989; Kline, 2011; MacCallum & Browne, 1993).⁴² While there is no theoretical restriction on the number of measures a construct should have, in practice (also confirmed by Monte Carlo simulation studies), accommodation of large number of measures (per construct) usually encounter global goodness of fit issues—that is a greater discrepancy between the implied and observed covariance matrices, implying correctly specified models as not so good fits to data (Byrne, 2010; Kenny & McCoach, 2003; Matsunaga, 2008). For this reason, in CBSEM applications, 3 to 5 indicators per construct is deemed optimal in

⁴¹ A formative construct is a construct that is formed by combining a set of measures to add meaning to the construct; a formative construct does not exist without its measures (Chin, 1998). This may be a reason why formative constructs are uncommon in strong positivistic disciplines such as psychology (positivistic ontology holds that reality exists out there without the measures and the observer).

⁴² The reason for this is that the CBSEM approach does not make the somewhat counter-positivistic assumption that a construct (factor) is a mere composite of its measures (Mulaik, 2009). Strictly speaking the factor scores are indeterministic in CBSEM, much same way as the factor scores are indeterministic in common factor analysis (Mulaik, 2009). However, if prompted, software packages such as AMOS produce factor scores using certain assumptions (Byrne, 2010).

most applications (Bollen, 1989; Byrne, 2010; Kline, 2011).⁴³ Hence, in CBSEM applications where larger numbers of measures are used to operationalise a latent variable, a strategy known as “measurement item parcelling” is used. In item parcelling used in SEM, measurement items are aggregated (typically the average is taken) to form a fewer number of indicators per latent variable (Bandalos & Finney, 2001; Byrne, 2010; Matsunaga, 2008). In this research, the parcelling strategy was used to reduce the number of indicators used to operationalise the constructs. While there are several parcel-building algorithms (e.g. the factorial algorithm, the random algorithm, the correlational algorithm, and the radial algorithm), the researcher used the factorial algorithm (Matsunaga, 2008) for parcel-building.⁴⁴

As it is important to inform the reader that item parcelling is prevalent in applications that involve CBSEM. The following statement paraphrased from Bandalos and Finney (2001) typifies how common item parcelling is in CBSEM (note that the above authors as well as many other authors use the terms SEM and CBSEM interchangeably).

We found that of 317 applied SEM or CFA studies, 62 (19.6%) employed some type of parceling procedure. More specifically, we found the following percentages with each journal: Journal of Educational Measurement, 60%; Journal of Education Psychology, 23%; Applied Psychological Measurement, 25%; American Educational Research Journal, 33%; Educational and Psychology Measurement, 18%; Structural Equation Modelling, 13%; and Journal of Marketing Research, 9%. (Bandalos & Finney, 2001 p.269)

⁴³ In their review of 75 articles on the application of CBSEM in operations management research in A grade journals, Shah and Goldstein (2006) report some useful statistics: the average sample size = 202, the average number of parameters to be estimated = 37.5, and the average number of measures used to operationalise all the construct in the model = 16.3. The respective figures in the author’s study (320, 40 and 15) compare favorably with these main figures.

⁴⁴ Review of the literature (e.g. Bandalos & Finney, 2001; Byrne, 2010; Matsunaga, 2008) on item parcelling leads one to conclude that there are no strict rules on item parcelling (item parcelling seems to be as much an art as a science), which perhaps explains why item parcelling is not being viewed favourably by its critiques. The researcher therefore used the following heuristic, which is consistent with what other researchers have been practicing. “If all latent variables contain more than 5 measures, consider item parcelling, keeping the reduction ratio (e.g. 2:1) to be the same across all latent variables, as much as possible (maintaining the same reduction ratio will not be possible if each latent variable possesses a very different number of items than the other, such as the case of the researcher’s model), keeping in mind that one should keep the number of parcels between 3 to 5. However, if only one or few latent variables contain more than 5 measures, item parcelling should be restricted to those latent variables only”.

The results of the empirical analysis are shown from next section onwards. The model development, survey instrument development, survey instrument content validation, sampling, pilot testing, and data collection were covered in Chapter 4.

6.3. DESCRIPTIVE STATISTICS OF SURVEY DATA

Out of the 1240 questionnaires dispatched to the 31 factories (see Chapter 4 for details), 332 were returned with responses (from all 31 manufacturing facilities), resulting in a raw response rate of 29.6%. Of the 332 responses received 14 were discarded as these had a large number of unanswered questionnaire items; any completed questionnaire that had more than 12 unanswered questionnaire items (i.e. 30% of questionnaire items) were regarded as unusable for the research. Thus the usable number of responses was 318, resulting in a net response rate of 28.4%.

Figure 6.2 depicts descriptive statistics pertaining to the respondents. It is not surprising that female respondents outnumber the male respondents, as about 90% of the workforce in the apparel industry in Sri Lanka are females (Arsenault et al., 2009; Safa, 1981). The results also show that the respondents possess a satisfactory education level (note that the GCE (AL) qualification in Sri Lanka is equivalent to NCEA level 3 qualification in New Zealand).

Figure 6.2 shows that both blue collar (57%) and white collar (43%) employees are equally (approximately) represented in the survey responses. Given that the 1240 questionnaires were distributed among blue and white collar employees on a 50-50 basis (in each factory), the results show that neither the blue collar nor the white collar employees are over-represented in the responses received. Figure 6.2 also shows that 205 out of 318 (64%) of respondents have over 5 years of work experience in the apparel industry.

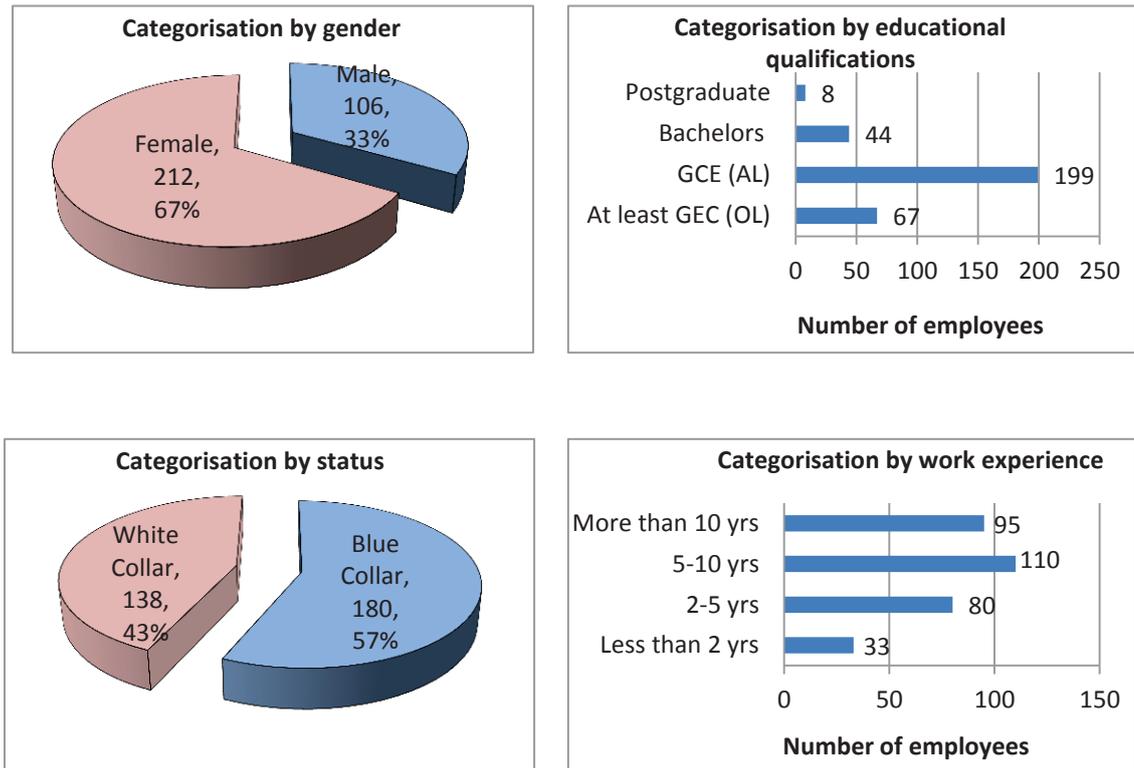


Figure 6.2: Presentation of descriptive statistics of the respondents

6.4. TESTING THE VALIDITY OF THE CONSTRUCTS

6.4.1. Testing the Survey Responses for the Absence of Substantial Common Method Bias

Common method bias (or simply method bias) causes systematic errors that generate Type I and Type II errors (Chang, Witteloostuijn, & Eden, 2010). As mentioned in Chapter 4, Harman's single factor test (Podsakoff & Organ, 1986) was used to verify the absence of common method bias in the survey responses. Harman's single factor test seeks whether or not a single factor (component) extracts the variability of all the questionnaire items (40 of them in the researcher's study) in a measurement instrument. If a single factor extracts the variability of the questionnaire items, according to Harman's single factor test, the responses are treated as suspect (biased). The researcher used principal components analyses (PCA) method to determine how many factors (components) are required to extract the variability of the 40 questionnaire items in the questionnaire. The PCA showed that as many as four components are required (the

scree plot is shown in Figure 6.3 below) to extract the variability of the questionnaire items.⁴⁵ This implies that the results do not suffer from substantial common method bias.

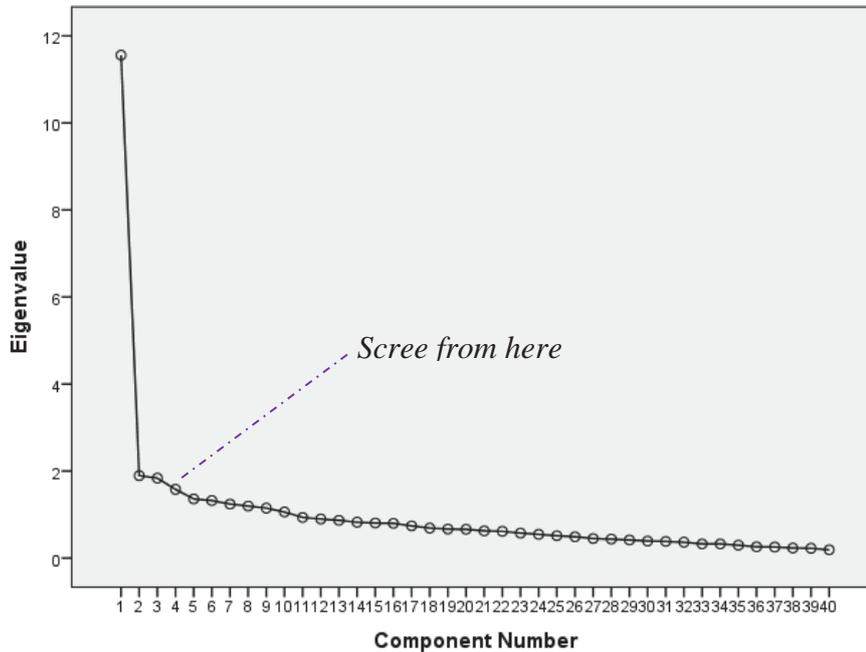


Figure 6.3: The scree plot

6.4.2. Testing for Unidimensionality of the Constructs

The first step used by the researcher in establishing the validity of the measurement scales used for each construct was the assessment of unidimensionality. The reader is reminded that in the questionnaire (details in Chapter 4): the construct Lean Manufacturing System is represented by 14 questionnaire items; the construct CI is represented by 11 questionnaire items; the construct Taguchi’s Quality Philosophy is represented by 7 questionnaire items; and the construct Manufacturing Process Outcomes is represented by 8 questionnaire items (40 items in total to represent 4 constructs). The scale unidimensionality was verified using PCA by taking questionnaire item scores belonging to each construct. For each construct, PCA extracted only one factor (eigenvalue > 1.0) from the measures, suggesting unidimensionality of the measurement scales. However, 6 questionnaire items (these have been strikethrough in Table 6.1) were removed due to low factor loadings (< 0.4).

⁴⁵ The eigenvalues of the four components are: 11.557, 1.895, 1.837, and 1.579 (also see Figure 6.3).

Two questionnaire items were removed from each construct but the construct Lean Manufacturing System (the factor loadings and internal consistency estimates for all 14 questionnaire items of this construct was found to be satisfactory). Table 6.1 depicts the factor loadings of the questionnaire items of each construct after the six questionnaire items have been excluded. The questionnaire items in Table 6.1 have been arranged in the *descending order* of factor loadings.

Table 6.1: Indicators of the Measurement Scales and Factor Loadings

Question No. in the Questionnaire	A Brief Description of Each Questionnaire Item (Question) in the Questionnaire	Indicator to Which a Question Belongs to After Parcelling	Factor Loading	Mean \pm SD
Lean Manufacturing System				
Q34	Develop exceptional people and teams to follow company's philosophy	L1	0.750	5.01 \pm 0.83
Q32	Process support the strategic objectives of our organisation	L2	0.746	5.09 \pm 0.61
Q39	Employees become multi-skilled through frequent job rotation	L3	0.695	5.00 \pm 0.88
Q31	Standardised methods to identify problems	L4	0.677	5.01 \pm 0.75
Q25	Visual control systems to indicate problems in the production floor	L5	0.674	5.30 \pm 0.77
Q23	Managing the production using "pull" production system	L1	0.668	5.14 \pm 0.77
Q40	Company provides opportunities for my growth and development	L2	0.665	5.41 \pm 0.73
Q33	We use cross-functional teams to solve the problems	L3	0.614	5.00 \pm 0.87
Q24	Organisation has a system that enables learning through experience	L4	0.611	5.13 \pm 0.74
Q18	Supplier relationships	L5	0.578	5.30 \pm 0.73
Q5	Maintain our plant in a clean and orderly manner	L1	0.560	5.34 \pm 0.70
Q30	Predictive and preventive maintenance program	L2	0.530	4.99 \pm 0.67
Q37	Use value stream map to achieve improvements	L3	0.517	4.94 \pm 0.87

Question No. in the Questionnaire	A Brief Description of Each Questionnaire Item (Question) in the Questionnaire	Indicator to Which a Question Belongs to After Parcelling	Factor Loading	Mean \pm SD
Q14	The ultimate judge of our products and services is customer	L4	0.437	5.56 \pm 0.67
CI				
Q17	Employees use appropriate tools and techniques to support CI	CI1	0.683	4.99 \pm 0.88
Q7	Ongoing assessment to that the organisation's structure and infrastructure support the corporate and departmental strategy	CI2	0.680	4.93 \pm 0.77
Q16	Managers lead by example	CI3	0.673	5.24 \pm 0.67
Q22	Employees understand department's strategies, goals and objectives	CI4	0.654	5.07 \pm 0.69
Q21	We attempt to continuously reduce the change-over time	CI1	0.649	5.40 \pm 0.62
Q4	Improvement tasks are embedded in employers' everyday activities	CI2	0.639	4.76 \pm 0.91
Q8	Company design the plant layout to improve the material flow	CI3	0.631	5.11 \pm 0.84
Q15	The mechanism used to enable CI effort in our company are monitored	CI4	0.562	5.23 \pm 0.68
Q3	Standardisation of process and task	CI1	0.506	5.21 \pm 0.80
Q11	The employees in our plant are rewarded appropriately			4.86 \pm 1.04
Q36	Employees are encouraged to learn from mistakes			4.90 \pm 0.84
Manufacturing Process Outcomes				
Q38	The risk and uncertainty that the final product will not meet customer requirement has been reduced by our company	PO1	0.697	5.00 \pm 0.70
Q6	Progress in reducing the manufacturing cycle time	PO2	0.678	5.16 \pm 0.85
Q35	Improvement in reducing new product development time	PO3	0.677	4.74 \pm 0.91
Q2	Effectiveness of product development	PO1	0.616	4.91 \pm 0.86
Q28	Progress in reducing internal scrap and rework	PO2	0.605	5.00 \pm 0.72
Q9	The customer complaints about product quality	PO3	0.532	5.11 \pm 0.77

Question No. in the Questionnaire	A Brief Description of Each Questionnaire Item (Question) in the Questionnaire	Indicator to Which a Question Belongs to After Parcelling	Factor Loading	Mean \pm SD
Q1	Effectiveness of process development			4.97 \pm 0.85
Q26	Unit cost of production compare to competitors			4.23 \pm 0.97
Taguchi's Quality Philosophy				
Q20	Any deviation from the target value as a loss to our company	T1	0.808	4.84 \pm 0.94
Q19	Any deviation from the target value as a loss to our external customer	T2	0.755	4.70 \pm 0.91
Q13	The term "quality" to mean little or no deviation from the target value	T3	0.556	4.97 \pm 0.64
Q27	Products robust under varying user conditions	T1	0.507	4.99 \pm 0.88
Q29	Quality cannot be achieved only through inspecting	T2	0.494	5.23 \pm 0.64
Q10	Get optimum process setting by changing OFAT (reverse coded)			4.89 \pm 0.88
Q12	Try to make our manufacturing process robust			5.11 \pm 0.75

6.4.3. Survey Item Parcelling Results

Then the questionnaire items were aggregated to reduce to a fewer number of measures, using the "factorial algorithm" (Matsunaga, 2008, p. 286). As an example for aggregation, the 14 questionnaire items that belonged to Lean Manufacturing System were reduced to 5 measures (L1 through to L5), as shown in Table 6.1. Staying with the construct Lean Manufacturing System to explain the factorial algorithm further, the first parcel (L1) of the said construct was created by taking the average of the scores of the questionnaire items with the first highest, sixth highest and eleventh highest factor loadings (hence the average of the scores for Q34, Q23, and Q5); the second parcel (L2) was created by taking the average of the scores of the questionnaire items with the second highest, seventh highest and twelfth highest factor loadings (hence the average of the scores for Q32, Q40, and Q30), and so on. The reader may note that the factorial algorithm evenly distributes the item-specific components across the parcels

(Matsunaga, 2008; Rogers & Schmitt, 2004). The application of the factorial algorithm resulted in 5, 4, 3, and 3 measures for the constructs Lean Manufacturing System, CI, Taguchi's Quality Philosophy, and Manufacturing Process Outcomes respectively (Table 6.1).

The scores of the above 15 measures were examined for normality (see Appendix E) and independence using the normal probability plot and run chart respectively. None of the 15 normal probability plots and the 15 run charts indicated strong evidence of non-normality and non-randomness.

6.4.4. Testing Scale Reliability

Scale reliability is a precondition for validity of the constructs (Nunnally & Bernstein, 1994). There are three widely used reliability coefficients: Cronbach's coefficient alpha (α) (Cronbach, 1951), composite reliability coefficient (ρ) (Werts et al., 1974), and the average variance extracted (AVE) (Fornell & Larcker, 1981). All of these coefficients were determined using SPSS software. The reader may note that the values of the last two reliability coefficients ρ and AVE were obtained after conducting CFA/CBSEM (covered later) as it is not possible to determine these values otherwise (Chin, 1998).

Table 6.2 depicts the above mentioned reliability coefficients taking into account "with item parcelling" and "without item parcelling" scenarios (without item parcelling scenario, as justified later, is given as a baseline only). Comparing the values of the coefficients for the four constructs with minimum values prescribed (Table 6.2), it becomes clear that all but the construct *Taguchi's Quality Philosophy* meet the minimum values prescribed for an established construct. Given that Taguchi's Quality Philosophy is in fact a relatively new construct, the Cronbach's α value of 0.60 obtained was deemed acceptable (Nunnally & Bernstein, 1994). Moreover, it is well documented that Cronbach's α can significantly underestimate scale reliability if a condition known as Tau equivalency is violated; Tau equivalency approximately translates to having to have equal variance across all indicators (measures) of the construct (Graham, 2006; Peterson & Kim, 2013). In this research the variance of all three indicators of Taguchi's Quality Philosophy was not equal, which explains why the reliability of Taguchi's Quality Philosophy is under estimated through Cronbach's α . The reader will note that

the values of the reliability coefficients ρ and AVE of Taguchi's Quality Philosophy exceed the minimum values prescribed for a mature construct. For these reasons it was considered that the scale of this construct is sufficiently reliable.

Table 6.2: Measures of Scale Reliability

Construct	With Item Parcelling				Without Item Parcelling			
	No. of Indicators	Cronbach's Alpha	AVE	Composite Reliability	No. of Indicators	Cronbach's Alpha	AVE	Composite Reliability
Lean Manufacturing System	5	0.84	0.62	0.83	14	0.89	0.40	0.93
CI	4	0.75	0.58	0.80	9	0.82	0.40	0.90
Manufacturing Process Outcomes	3	0.69	0.60	0.75	6	0.71	0.41	0.85
Taguchi's Quality Philosophy	3	0.60	0.54	0.74	5	0.64	0.41	0.82
Notes:								
(a) Without item parcelling scenario (not used) is shown for baseline purposes only.								
(b) The minimum allowable values for Cronbach's coefficient alpha and composite reliability coefficient (α) are 0.70 for an established (mature) construct and 0.60 for a new (or emerging) construct. The minimum allowable value for AVE is 0.50 (sometimes lower values may also be acceptable). For more details of the cut-off values of Cronbach's α , ρ , and AVE see Nunnally & Bernstein (1994); Werts, Linn and Jöreskog (1974); and Chin (1998) respectively.								

6.4.5. Confirmatory Factor Analysis to Establish Factorial Validity of the Constructs

Having established scale reliability, the validity of the constructs is assessed next. Confirmatory Factor Analysis (CFA), a special case in CBSEM where every construct in the model is correlated to every other construct, was conducted to establish factorial validity (Byrne, 2010). Factorial validity is an important aspect of construct validity (Bollen, 1989; Nunnally & Bernstein, 1994); it establishes that the constructs (factors), as operationalised by their measurement scales, do represent (in a factorial/statistical sense) what they purport to represent (Bollen, 1989; Nunnally & Bernstein, 1994). It is important to note that factorial validity is only one aspect (though an important one) of construct validity (Nunnally & Bernstein, 1994).

In the user friendly CBSEM software package AMOS, CFA can be performed by replacing the single headed arrows (causal paths) in Figure 6.1 (or Figure 6.4) with double headed arrows.⁴⁶ This also raises a perennial oddity in SEM—equivalent models—where two models do show the exact same global goodness of fit, irrespective of the data (Lee & Hershberger, 1990; Steiger, 2001; Stelzl, 1986). Using the rules prescribed by Lee and Hershberger (1990) it can be shown that the model which was used for CFA in this research and the theoretical model (Figure 6.1 and Figure 6.4) are equivalent models.

Table 6.3 shows the extent to which the CFA model as well as the theoretical model (Figure 6.1) fit to data (after item parcelling and before item parcelling) in a covariance sense; the covariance fit is formally known as the “global goodness-of-fit” (Byrne, 2010; Kline, 2011). The frequently used global goodness-of-fit measures to assess the covariance fit are covered in Table 6.3.

Table 6.3: The Global Goodness-of-Fit Statistics of the CFA and the Theoretical Model

Indicator	Value When Items are Parcelled	Value When Items are not Parcelled	Prescribed Cut-off Values
Discrepancy (χ^2)/df	143.391/84 = 1.71	1050.963/523 = 2.01	Less than 3 desired
RMSEA	0.047	0.056	≤ 0.05 for a good fit; > 0.05 and < 0.08 for a satisfactory fit
CFI	0.963	0.834	> 0.90 for good fit
NFI	0.918	0.721	> 0.90 for good fit
PCLOSE	0.621	0.02	> 0.50 for a good fit
Note: Based on the results shown in this table, the model with parcelled items was treated as the model for further analysis. For prescribed cut off values of global goodness-of-fit measures see Byrne (2010).			

As shown in Table 6.3, the global goodness-of-fit indicators for the CFA model and the theoretical model are a good fit to data (in a covariance sense), when the questionnaire

⁴⁶ The only difference between Figure 6.1 and Figure 6.4 are that the former shows all the linear structural relationships (i.e. the structural relationships involving the constructs and their measures as well as the structural relationships between the constructs) while the latter shows only the structural relationships between the constructs. Once the validity of the measures has been established, to keep things simple, it was decided that there is no need to show the full model when the relationships between the constructs are examined (i.e. examining test results on the research hypotheses).

items are parcelled; when they are not, the covariance fit (the global goodness-of-fit) suffers, a condition well known to CBSEM users. This justifies the use of item parcelling.

Having established factorial validity through CFA, the convergent and discriminant validity of the constructs, another important aspect in construct validity, was established by tabulating the correlations and cross-correlations between the constructs (latent variables) and the indicators (measures) of the constructs. Table 6.4 shows the loadings (correlations) and cross-loadings (cross correlations) concerned.

6.4.6. Convergent Validity and Discriminant Validity of the Measures

An indicator (or a measure) of a construct is said to be showing convergent validity if that indicator is strongly correlated (this correlation is known as the loading) with its assigned construct (Byrne, 2010; Chin, 1998). An indicator (or a measure) of a construct is said to be showing discriminant validity if the correlations between the indicator and the other constructs to which the indicator is not assigned to (these correlations are known as cross-loadings) are not as strong as the correlation between the indicator and its assigned construct (i.e. loading) (Byrne, 2010; Chin, 1998).

Table 6.4: The Factor Loadings and Cross Loadings

Indicator	Construct			
	Lean Manufacturing System	CI	Manufacturing Process Outcomes	Taguchi's Quality Philosophy
L1	0.81	0.68	0.58	0.36
L2	0.78	0.65	0.57	0.28
L3	0.78	0.61	0.60	0.33
L4	0.79	0.58	0.59	0.33
L5	0.73	0.62	0.45	0.41
CI1	0.65	0.78	0.54	0.34
CI2	0.56	0.73	0.50	0.23
CI3	0.60	0.76	0.48	0.39
CI4	0.61	0.74	0.49	0.34
PO1	0.58	0.54	0.79	0.38
PO2	0.52	0.53	0.76	0.33
PO3	0.45	0.45	0.73	0.40
T1	0.34	0.32	0.39	0.82
T2	0.28	0.23	0.33	0.74
T3	0.19*	0.29	0.34	0.57

Notes:

(a) All the above correlations were significant at 0.001 level except the one with the asterisk (*), which is only significant at 0.05 level.

(b) L1 through to L5 are the indicators of Lean Manufacturing System; CI1 through to CI4 are the indicators of CI, PO1 through to PO3 are the indicators of Manufacturing Process Outcomes, and T1 through to T3 are indicators of Taguchi's Quality Philosophy.

Based on the loadings (the highlighted correlation) and cross-loadings (the non-highlighted correlations) shown in Table 6.4, it becomes clear that the indicators of the constructs show convergent and discriminant validity.

Having established scale reliability and having established factorial validity, convergent validity, and discriminant validity, it is concluded that the 15 measures are a valid operationalisation of the constructs (Byrne, 2010; Nunnally & Bernstein, 1994). All of

the above forms of validities converge to what is known as “construct validity” in psychometrics (Messick, 1995; Nunnally & Bernstein, 1994).⁴⁷

As the construct validity means that the constructs are good for manipulation the next section (section 6.5) shows the structural relationships between the constructs along with test results on the six research hypotheses. These test results have also been discussed from a theoretical and practical perspective in the next section.

6.5. TEST RESULTS ON THE RESEARCH HYPOTHESES AND THE DISCUSSION

It was shown earlier that the theoretical model is a good fit to data (see Table 6.3 for test results). Figure 6.4 shows the estimated structural coefficients between the constructs; except for the double headed arrow showing the correlation between the Lean Manufacturing System and Taguchi’s Quality Philosophy, all other coefficients are standardised regression coefficients.

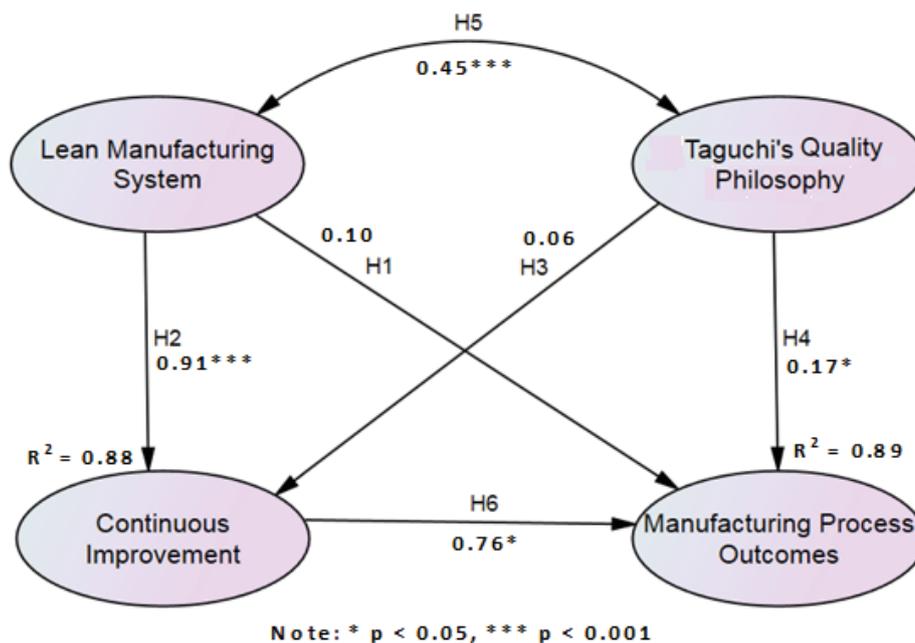


Figure 6.4: The structural relationships between constructs and parameter estimates

⁴⁷ Even the validity of survey contests (Chapter 4), referred to as content validity in psychometrics, is subsumed in construct validity (Messick, 1995; Nunnally & Bernstein, 1994).

Figure 6.4 shows that of the six hypotheses posited two hypotheses are not supported by data ($p > 0.05$). These two hypotheses are as follows:

H1: “A Lean Manufacturing System has a direct positive effect on Manufacturing Process Outcomes”

H3: “Taguchi’s Quality Philosophy has a direct positive effect on Continuous Improvement”

The implications of the two non-supported hypotheses are discussed in turn.

Not supporting H1 implies that, in the setting in which the data were collected (apparel manufacturing), the Lean Manufacturing System has no direct effect on Manufacturing Process Outcomes. However, Lean Manufacturing System exerts a strong and significant effect on Process Outcomes through the mediating variable CI. This empirically demonstrates the mediating role that CI plays within the Lean Manufacturing System \rightarrow Manufacturing Process Outcomes relationship. This conclusion is based on the high standardised regression coefficients in the following paths: Lean Manufacturing System \rightarrow CI (0.91, $p < 0.001$), and CI \rightarrow Manufacturing Process Outcomes (0.76, $p = 0.035$).

From a practical perspective, the strong mediating role played by CI in the causal path Lean Manufacturing System \rightarrow Manufacturing Process Outcomes could imply that for manufacturing firms that espouse Lean, CI activities that are perceived to be improving the process outcomes are a manifestation of Lean. The extant literature (e.g. Bhuiyan & Baghel, 2005; Bhuiyan, Baghel, & Wilson, 2006; Chen et al., 2010; Shah & Ward, 2003) does support the hypothesis that CI is an integral component of a Lean Manufacturing System, which explains the strong support for H2.

A positive (albeit small) causal predictive relationship was found in the path Taguchi’s Quality Philosophy \rightarrow Manufacturing Process Outcomes (0.17, $p = 0.041$), this time without any significant mediation through CI. Given that Taguchi’s Quality Philosophy was found to be positively correlated with the Lean Manufacturing System (0.45, $p = 0.000$), and given that Taguchi’s Quality Philosophy is directly related to Manufacturing Process Outcomes, it can be argued that Taguchi’s Quality Philosophy is being viewed by Lean practitioners as a philosophy that is acceptable to their

manufacturing practices. The lack of support for H3 implies that CI does not mediate the causal relationship between Taguchi's Quality Philosophy and Manufacturing Process Outcomes. In practice Taguchi methods are frequently used in CI projects (with or without the banner Lean Six Sigma) to reduce product or process variability (Park & Ha, 2005; Shang, Li, & Tadikamalla, 2004; Taguchi et al., 2005). Taguchi's Quality Philosophy, the primary element of Taguchi's robust parameter design approach (see sections 3.4.1 and 3.4.2 for details), is based on the notion that achieving high system quality levels economically, requires "quality to be designed", implying pushing quality back to the product/process design stage (Gunter, 1987; Unal & Dean, 1991). Improving the product or process by applying statistically designed experiments to solve existing quality problems (with or without the banner Lean Six Sigma) is not what Taguchi advocated, although Taguchi himself had to help the Japanese industry in solving existing and ongoing quality problems associated with products and processes (Roy, 2010; Taguchi & Clausing, 1990).

In essence Taguchi's robust design approaches mainly focus on offline quality control (quality by design as opposed to quality by control) (Gunter, 1987; Roy, 2010; Taguchi & Clausing, 1990; Unal & Dean, 1991). As shown in the literature review (Chapter 3), implementing Taguchi methods is a simple and less costly strategy of achieving robustness in the products and processes (hence quality) on two counts. Firstly Taguchi methods enable firms to manufacture a high quality product upfront using less resources (e.g. less financial expenditure as opposed to buying expensive raw material and machinery to make the product and processes robust). Secondly, because Taguchi methods aim at producing the product (or process) the right first time, they greatly eliminate the need to correct problems found in the products later, through capital intensive quality improvement projects such Lean Six Sigma projects (Hoerl & Gardner, 2010; Snee, 2010). Through the questionnaire items on Taguchi's Quality Philosophy the respondents may have perceived that this philosophy has some merit in developing products to achieve manufacturing process outcomes (a significant H4 supports this) but not in a CI context. One can also argue that non-support of H3 could be due to respondents not having experience in using Taguchi methods to improve quality in CI projects such as Lean Six Sigma.

The high R^2 for Manufacturing Process Outcomes (0.89) warrants an explanation as such high R^2 values are not very common in published studies (for two exceptions see Eskildsen & Dahlgard, 2000; and Jayamaha et al., 2014) in social sciences. The high R^2 can be attributed to employee's perceived knowledge on the actual outcomes. As a part of the visual management system of their own production management system, all apparel manufacturing plants from which the data were collected were required to visually display (e.g. through histograms, trend lines etc.) how they have been achieving Lean outcomes. In conducting fieldwork (Taguchi-style experiments) by the researcher in one of the manufacturing factories, it was found that visual displays that the manufacturing plants have been displaying (within the case study factory and elsewhere) showed positive trends over the last three years (see the previous chapter). Therefore it is quite possible that the respondents may have had perceived that the Lean production systems of their respective plants have been doing well, thus resulting in a high R^2 for Manufacturing Process Outcomes.

Finally, Table 6.5 depicts the research questions answered and the specific research objectives achieved thus far (up to this chapter). In formulating a theoretical model (Chapter 4), the researcher proposed how Taguchi's Quality Philosophy is theoretically related to Lean. In this chapter the researcher confirmed the validity of her theoretical model (the model was found to be a good fit to data). This answered the first research question (RQ1). In the process of validating the model the researcher also answered the second research question (RQ2), within the positivistic approach that researcher adopted. The validity of the model including a significant correlation between the two constructs Taguchi's Quality Philosophy and Lean Manufacturing System ($r = 0.45$ and $p < 0.001$, as shown in Figure 6.4) implies that Taguchi's Quality Philosophy is accepted by the practitioners of Lean philosophy in the apparel industry as a way of enhancing Manufacturing Process Outcomes. Answering both RQ1 and RQ2 completed achievement of the first research objective.

Table 6.5: The Research Questions Answered and the Research Objectives Achieved

Research Questions Answered	Specific Research Objectives Achieved
<p>RQ1: How does Taguchi’s Quality Philosophy theoretically relate to Lean, in improving the operational performance?</p>	<p>Objective 1: To formulate and statistically test a theory that predicts and explains how <i>Taguchi’s Quality Philosophy</i> and <i>Lean</i> management</p>
<p>RQ2: What is the acceptance of Taguchi’s Quality Philosophy by the practitioners of Lean philosophy in the apparel industry?</p>	<p>jointly contribute towards improving the operational performance in a mature Lean apparel manufacturing environment.</p>

6.6. CHAPTER CONCLUSION

This chapter was mainly dedicated for testing the six research hypotheses (which together constituted the researcher’s theoretical model), which in effect answered the researcher’s first two research questions. This also meant that the first research objective (see Table 6.5) was achieved. Review and selection of the appropriate SEM technique (CBSEM) was also an outcome of this chapter.

The theoretical model (Figure 6.4) was found to be a good fit to the data, in terms of the major global goodness-of-fit indices used in CBSEM (Blunch, 2008; Byrne, 2010). This suggested that the researcher has correctly specified her model. Four out of the six of the hypotheses were supported by data. The implications of the two hypotheses that were not supported by data were discussed from a theoretical and practical perspective. However, the impact of Taguchi’s Quality Philosophy on the Lean Manufacturing System was found to be small from a practical stand point. It was suggested that this could be due to lack of experience (on the part of frontline workers and their managers) in improving quality (more specifically reduce variation) through design of experiments. In the next two chapters (Chapter 7 and Chapter 8) the researcher will examine what happens when Taguchi’s Quality Philosophy is put into practice, through designed experiments (Taguchi methods) at the case study factory.

CHAPTER 7

OUTCOMES FROM THE ON-FIELD EXPERIMENTS

“If your experiment needs a statistician, you need a better experiment”

—Ernest Rutherford

7.1. INTRODUCTION

This chapter on results and discussion is focussed towards answering the third research question (RQ3): *What are the statistical and operational merits and demerits (if any) of using Taguchi methods over conventional robust design experimental methods in solving important quality problems in apparel manufacturing?*

Section 7.2 shows the results of the studies that preceded the experiments. Section 7.2.1 covers the findings on the scientific studies that were conducted to verify the precision of the measurement system that was used to measure the primary response variable of the main experiment: *back-coverage*. Section 7.2.2 covers the assessment of the stability (predictability) and capability of the existing manufacturing sub-process (sewing) in which the variation reduction/quality improvement (QI) problem exists. Ensuring that the measurement system is precise enough for conducting experiments and ensuring that the process is not subjected to special cause variation (meaning that the process is stable) are two important prerequisites in DoE (Box et al., 2005; Montgomery, 2013).

Section 7.3, one of the two main sections of this chapter, covers the results of the main experiment. Section 7.4, the other main section of this chapter, covers the discussion on the results given in the previous section. Both, sections 7.3 and 7.4 are important sections because these sections not only answer the research question (RQ3) under consideration but they also provide evidence to support that Taguchi style robust parameter design (RPD) experiments have the potential to solve critical variation/quality problems. This in turn legitimises the final research question (RQ4), which is answered in the next chapter. As mentioned elsewhere (section 5.3.3), the quality/variation problems that were selected for studying were problems the managers (and their operating staff) of the Lean case study organisation were unable to resolve

successfully using standard Lean tools known to them. Finally, section 7.5 provides a chapter summary and a very brief overview of the next chapter.

7.2. FIELD STUDIES THAT PRECEDED THE EXPERIMENTS

As mentioned in a previous chapter (section 5.3.3) the most important QI problem that the managers faced was reducing the high variability of the back-coverage (measurement) of a particular design of Thongs produced for upmarket female customers. As mentioned earlier, because back-coverage is a physical measurement (Figure 5.8b), the variability of the manufacturing process based on the quality characteristic “back-coverage” was studied using variable control charts; these are shown and discussed in this section.

Understanding the variation of the process so as to ascertain whether it is subjected to just common cause variation or whether special cause variation has also affected the process is very fundamental in statistical thinking (Britz et al., 2000; Deming, 2000; Hoerl & Snee, 2012). The RPD experiments covered in this section were aimed at reducing common cause variation economically.

7.2.1. The Analysis of Results of the Gauge R&R Study

The Gauge R&R study comes first because it is necessary to make sure that the measurement system variability itself is consistent and comparably small, relative to process variability. Table 7.1 depicts the 60 back-coverage measurements, taken by two operators, on 15 pieces of garments, measured twice on two separate occasions. The measurements were taken in the randomised pattern given by the software package (Minitab 16).

Table 7.1: The Back-Coverage Measurement Data

Run Order	Piece No.	Operator	Measurement (Inches)	Run Order	Piece No.	Operator	Measurement (Inches)
1	12	1	1.9370	31	9	1	2.2285
2	7	1	1.8140	32	5	1	1.9665
3	6	1	2.1880	33	14	1	1.8200
4	9	1	2.1610	34	12	1	1.8125
5	13	1	2.2060	35	2	1	1.5180
6	5	1	1.9440	36	15	1	2.2560
7	3	1	1.9910	37	3	1	2.1735
8	15	1	2.2020	38	8	1	1.7835
9	8	1	1.8650	39	13	1	2.1775
10	2	1	1.5190	40	11	1	2.4515
11	4	1	2.2110	41	4	1	2.3445
12	1	1	1.9060	42	6	1	2.2855
13	10	1	2.1055	43	1	1	1.8480
14	11	1	2.5575	44	10	1	2.0665
15	14	1	1.9835	45	7	1	1.7925
16	3	2	2.1095	46	12	2	1.8040
17	10	2	1.9935	47	8	2	1.6125
18	6	2	2.2085	48	10	2	1.9330
19	12	2	1.8600	49	4	2	2.4295
20	5	2	2.0140	50	13	2	2.2515
21	4	2	2.3050	51	7	2	1.7755
22	11	2	2.4330	52	1	2	1.9040
23	14	2	1.9720	53	5	2	1.9585
24	9	2	2.0180	54	15	2	2.3405
25	1	2	1.9075	55	14	2	1.9280
26	2	2	1.4320	56	9	2	2.0155
27	13	2	2.0890	57	3	2	2.2325
28	7	2	1.8195	58	6	2	2.3395
29	8	2	1.7260	59	11	2	2.4700
30	15	2	2.1005	60	2	2	1.4950

The results of the Gauge R&R study based on the analysis of variance (ANOVA) are shown in Figure 7.1 (the alternative method based on \bar{x} and R provided very similar

results). Figure 7.1 shows that the operator and the sample \times operator interaction terms are statistically insignificant ($p > 0.05$) at 5% significance level.

Source	DF	SS	MS	F	P
Sample	14	3.60381	0.257415	38.4931	0.000
Operator	1	0.00677	0.006773	1.0129	0.331
Sample * Operator	14	0.09362	0.006687	1.3434	0.241
Repeatability	30	0.14933	0.004978		
Total	59	3.85354			

Alpha to remove interaction term = 0.25

Gauge R&R

Source	VarComp	%Contribution (of VarComp)
Total Gauge R&R	0.0058354	8.52
Repeatability	0.0049778	7.27
Reproducibility	0.0008576	1.25
Operator	0.0000029	0.00
Operator*Sample	0.0008547	1.25
Part-To-Part	0.0626819	91.48
Total Variation	0.0685173	100.00

Process tolerance = 0.5

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gauge R&R	0.076390	0.45834	29.18	91.67
Repeatability	0.070554	0.42332	26.95	84.66
Reproducibility	0.029285	0.17571	11.19	35.14
Operator	0.001694	0.01017	0.65	2.03
Operator*Samples	0.029236	0.17542	11.17	35.08
Part-To-Part	0.250363	1.50218	95.65	300.44
Total Variation	0.261758	1.57055	100.00	314.11

Figure 7.1: Gauge R&R results based on the ANOVA method

Furthermore, the results show that the % contribution from part-to-part is 91.48% while the % contribution from Gauge R&R is 8.52%. The results also show that the % study variation of total Gauge R&R study is 29.18%. These results show that while the measurement system is not ideal, it is nonetheless acceptable, based on the American Automotive Industry Action Group (AIAG, 2010) guidelines. AIAG guidelines stipulate the following: (a) $< 1\%$ contribution from Gauge R&R is ideal and 1-9% contribution is acceptable (this study reported a figure of 8.52%); (b) $< 10\%$ Study variation is ideal,

10-20% is acceptable, 20-30% is marginal but acceptable if it is not economically feasible to improve the measurement system (this study reported a figure of 29.18%) (AIAG, 2010; Wheeler, 2009). The reader is reminded that the above results were obtained after the researcher made substantial improvements to the existing measurement system (details in section 5.4.1).⁴⁸

Figure 7.2 shows the pack of six graphs that Minitab produced for the Gauge R&R study, based on the ANOVA method. Each graph in Figure 7.2 is described and interpreted in turn.

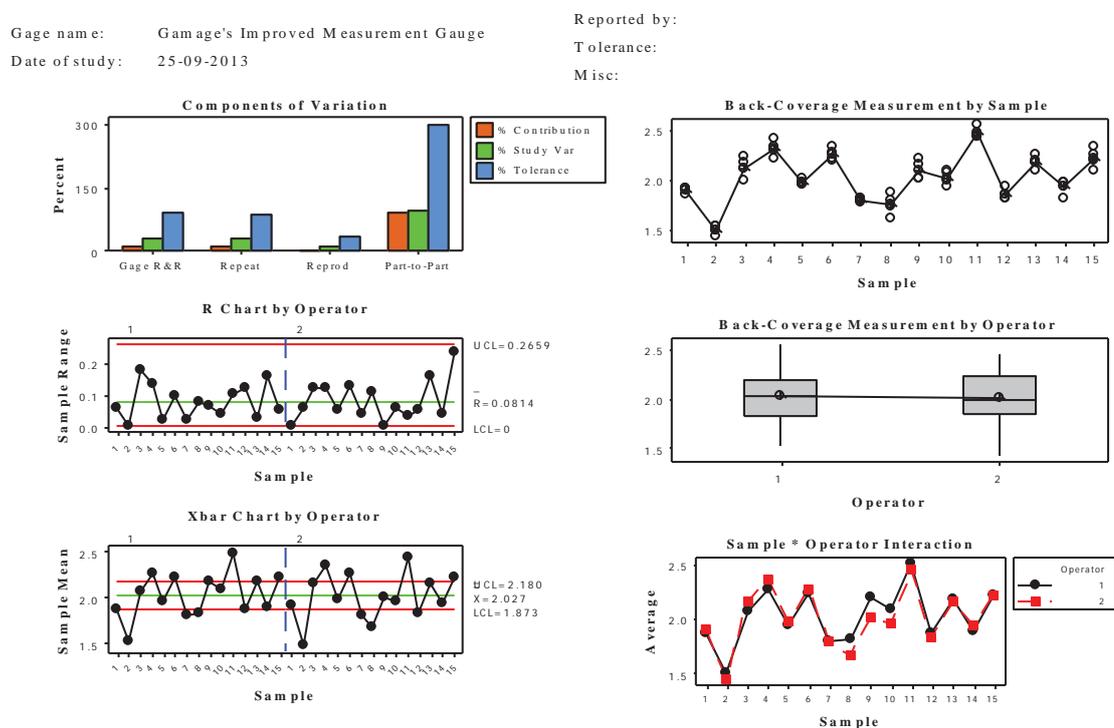


Figure 7.2:The graphical plots of the Gauge R&R study based on the ANOVA method

The ‘components of variation graph’ shows the variation due the measurement gauge (Gauge R&R), as well as part-to-part variation (meaning actual variation from one piece of garment to another). The graph also shows the Gauge R&R variation partitioned into its two constituents: repeatability and reproducibility; repeatability is the variation that results in repeated measurements of the same measurement taken by the same operator

⁴⁸ If anything the results show how difficult it is to obtain a precise measurement from a garment which are not rigid objects like automotive parts.

using the same measurement gauge while reproducibility is the variation due to different operators taking the same measurement using the same gauge (Hare, 2012; Montgomery, 2009). The component of the variation graph shows that part-to-part variation is the dominant source of variability, which basically implies that given the degree of part-to-part variation, the measurement gauge is able to produce measurements that are repeatable and reproducible (more on this follows).

The R chart by operator shows the operator consistency based on the range (R). The range R represents the difference between the largest and smallest measurements of each part for each operator. The R chart shows that there are no points outside the control limits. This suggests that operators were consistently measuring the back-coverage measurements because the difference between the highest measurement and lowest measurement is small (within control limits) relative to study variation (measurement system variation). Again this is an indication that the measurement is repeatable and reproducible (Amar, 2013).

The \bar{x} chart (the data points) shows the average measurements of each part for each operator. This compares the repeatability component to the part-to-part variation (the control limits are based on variation due to repeatability). There are many points that fall above and below the upper and lower control limits, which show that variation due to repeatability is low relative to part-to-part variation. This is a feature that is expected from a precise measurement system.

The box plot shows the consistency of the measurements and the variability among the two operators. The plot shows that the spread among measurements taken by the two operators are similar, with no outliers; the plot also shows that the two distribution means are approximately the same. This implies that there is low operator to operator variability.

The Sample \times Operator interaction plot shows the average back-coverage measurements taken by each operator for each part. The two lines do closely follow one another. This indicates that both operators appear to be measuring parts similarly, thus showing high reproducibility.

The Lessons Learnt by the QI Team on the Gauge R&R Study

It is important to note that although only two operators participated in the Gauge R&R study in testing the precision of the improved measurement system, and the total time spent on testing and improving the measurement system was only about 8 hours,⁴⁹ the entire QI team was indirectly engaged in the Gauge R&R study at the time the results were briefed by the researcher. The team learnt that the precision of a measurement has implications in quality control; for example, the team learnt that operator inconsistency and high random measurement variability have implications on product non-conformity rates based on the back-coverage measurement. Equally importantly, the team learnt that a Gauge R&R study is a necessary tool that needs to be added to their tool box.

7.2.2. Understanding Process Stability and Capability

Having established the adequacy of the precision of the measurement system, as mentioned elsewhere, the next step was to check the stability of the process. The \bar{x} and R control charts based on subgroups of size 5 (5 pieces of garments per subgroup) collected every hour for 22 consecutive operating hours is shown in Figure 7.3.

The \bar{x} and R chart shows that the variability of the process is stable and predictable for the particular quality characteristic (back-coverage) being selected (i.e. the process is not subjected to special cause variation; only common cause variation exists). The reader is reminded that the first four control chart tests prescribed by Nelson (1984) for special cause variation were used as control chart tests (Table 5.7 in section 5.4.2 Verifying Process Stability Using Control Charts).

⁴⁹ Approximately 3 hours was spent on testing the original measurement system, which involved 3 operators. Approximately 4 hours was spent on improving the measurement system, which involved two operators (another operator was used in the original test was not selected due to measurement inconsistency). Approximately 1 hour was spent on briefing the results and findings to the quality improvement team.

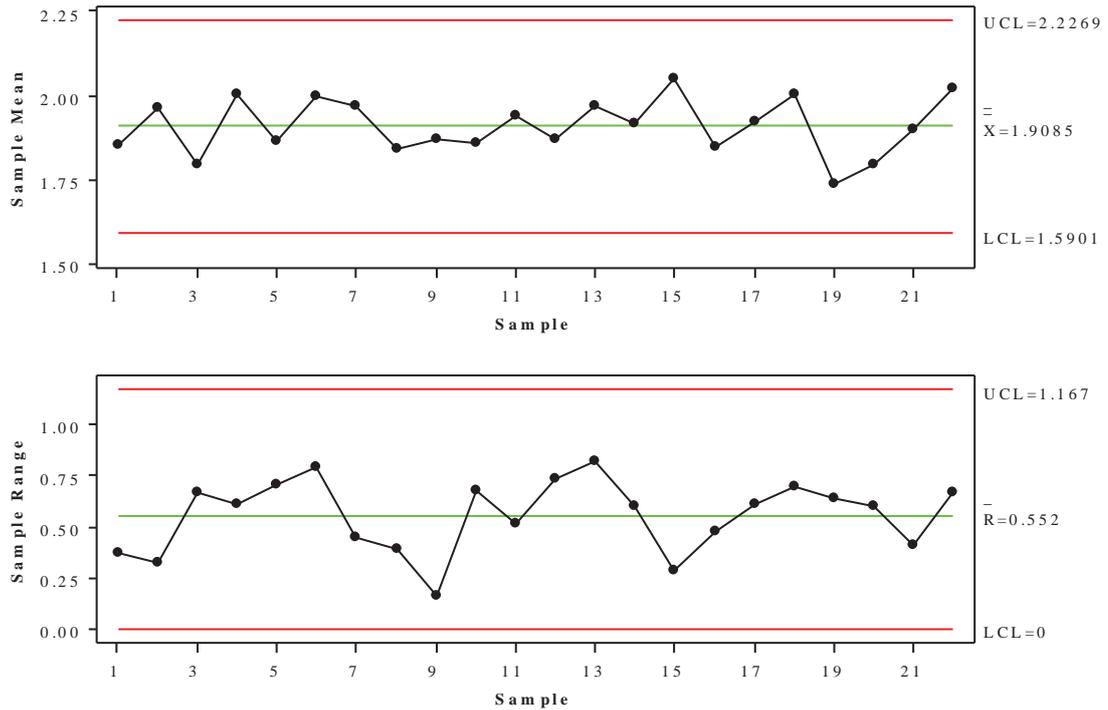


Figure 7.3: The \bar{X} and R chart for back-coverage measurement

Figure 7.4 shows important information related to process capability. The histogram shows that the distribution of measurements are approximately symmetric about the mean (1.9085) and that there are a sizable number of observations outside the specification limits, which translate to 263637 pieces of garments per million garments outside the specification limits (see the “observed performance” box). The red ‘bell curve’ shows a normal probability distribution about the mean, having a standard deviation of 0.2373, based on within subgroup variation (calculated by dividing the average range \bar{R} by control chart constant d_2). Based on this distribution, 296905 pieces of garments per million garments are expected to be outside the specification limits (see the “Exp. within performance” box)⁵⁰. The high proportions of nonconforming pieces of garments clearly imply low process capability.

⁵⁰ The black ‘bell curve’ (hash line) shows the normal probability distribution based on the overall standard deviation (i.e. the sample standard deviation based on the 110 observed values). Since the overall standard deviation should be used to assess the long term performance of the process (based on data collected over a longer period of time), the black bell curve and the expected overall performance data (in terms of nonconforming items per million) do not provide much useful information.

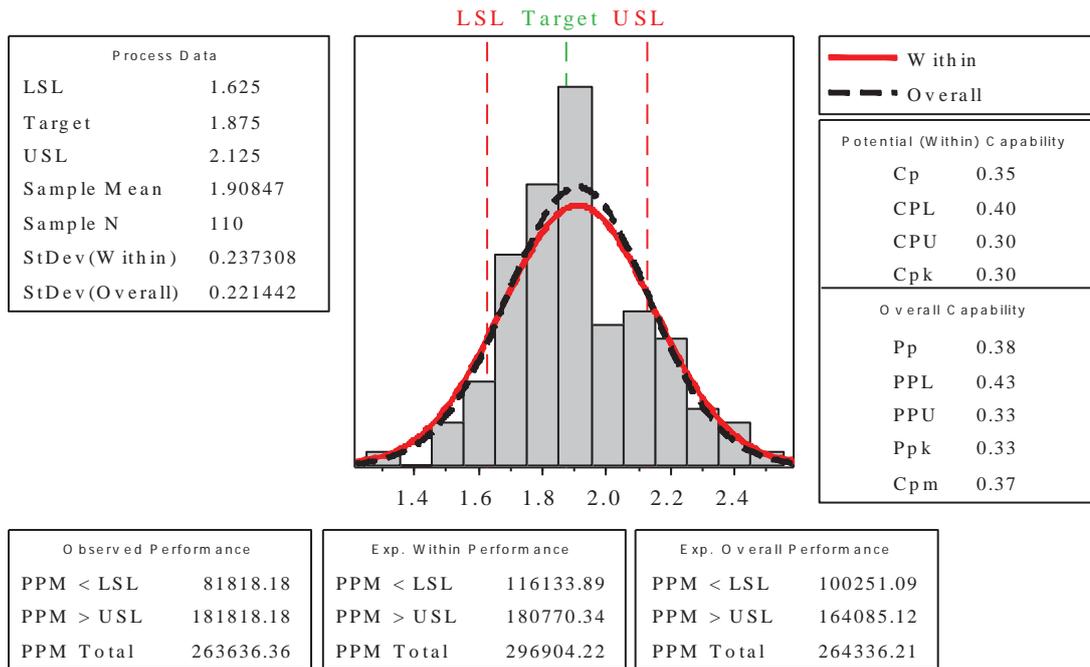


Figure 7.4: The process capability analysis results

The process capability indices C_p , C_{pk} , and C_{pm} are well below the industry standard of 1.33 for a capable process (Wheeler & Chambers, 2010). The fact that $C_{pk} < C_p$ suggests that the process centre is not at the target value (the middle of LSL and USL); however Figure 7.4 shows that the process is not significantly off centre. The major problem is high process variation (the standard deviation of the process is high at 0.2373), relative to the tolerance. This vindicates undertaking a designed of experiment to reduce this high process variation, thought to be caused because of the lack of robustness of the sewing sub-process to the variability of the noise factors identified by the QI team (details in section 5.3.4).

7.3. VARIATION REDUCTION/QI EXPERIMENTS

As mentioned earlier (section 5.5.2) the main experiment was set up as a crossed-array by combining two L8 orthogonal arrays for the inner and outer arrays; the response data for the back-coverage are shown in Table 7.2 (the factors and their levels were mentioned in Table 5.8 in section 5.5.1). The figures within parentheses show the random order in which each of the 64 trials were conducted. It was explained to the QI team that Taguchi methods are practical methods (hence practical convenience has to be

weighed against the statistical precision) and that randomisation, which is an integral part of a conventional DoE, is not strongly emphasised in this method (Roy, 2010). Box and Bisgaard (1987) emphasised the importance of randomisation of experimental runs to avoid biasing the results from unsuspected trends or patterns (i.e. unsuspecting confounding factor effects).

The two levels of each factor are represented by a ‘-1’ and a ‘+1’ in the matrix. The last four columns of the design matrix represent the mean, standard deviation, the signal to noise ratio (SNR), and mean square standard deviation (MSD) for the “target is best” (Ghani, Choudhury, & Hassan, 2004; Roy, 2010) optimisation criterion. The following SNR (eq. 7.1), frequently advocated by Taguchi (for target is best), was used in the study to derive the results.

$$SNR_{\tau} = -10 \log_{10} \left[\frac{S^2}{\bar{y}^2} \right], \text{ where } \bar{Y} \text{ is the mean response while } S^2 \text{ is the variance} \quad (7.1)$$

Table 7.2: The Back-Coverage Measurements Recorded During the Experiment

Inner Array (Control Factors)			Outer Array (Noise Factors)/Y (Inches)												Mean (\bar{Y})	Standard Deviation (S_Y)	SNR	MSD				
A	B	C	D	E	F																	
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	2.1293	0.4772	12.9906	0.2639
-1	-1	+1	+1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	2.0673	0.4495	13.2542	0.2138
-1	+1	-1	-1	+1	+1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	2.3619	0.5337	12.9189	0.4863
-1	+1	+1	2.2060 (04)	2.8400 (09)	2.2945 (24)	1.5860 (32)	1.7865 (34)	1.8850 (47)	1.6855 (47)	1.7475 (53)	1.8850 (52)	2.7510 (63)	1.8850 (52)	1.7475 (53)	1.8850 (52)	2.7510 (63)	1.8850 (52)	2.7510 (63)	2.1293	0.4772	12.9906	0.2639
-1	-1	-1	2.6880 (01)	1.8230 (16)	1.9510 (22)	1.4410 (28)	2.3585 (33)	1.8785 (45)	1.8785 (45)	1.7475 (53)	1.8785 (45)	2.6510 (61)	1.7475 (53)	1.7475 (53)	1.8785 (45)	2.6510 (61)	1.7475 (53)	2.6510 (61)	2.0673	0.4495	13.2542	0.2138
-1	+1	-1	2.0680 (07)	2.1695 (15)	2.8320 (23)	1.9720 (29)	2.4070 (40)	1.6770 (43)	1.6770 (43)	2.3950 (51)	2.3950 (51)	3.3745 (62)	2.3950 (51)	2.3950 (51)	1.6770 (43)	3.3745 (62)	2.3950 (51)	3.3745 (62)	2.3619	0.5337	12.9189	0.4863
-1	+1	+1	1.9505 (03)	2.6425 (12)	3.3378 (19)	2.0495 (27)	2.4315 (38)	1.9015 (48)	1.9015 (48)	2.3485 (49)	2.3485 (49)	2.4825 (59)	2.3485 (49)	2.3485 (49)	1.9015 (48)	2.4825 (59)	2.3485 (49)	2.4825 (59)	2.3930	0.4663	14.2066	0.4586
+1	-1	-1	1.8260 (08)	2.2195 (11)	2.2425 (20)	2.1530 (30)	2.0315 (37)	1.7595 (44)	1.7595 (44)	2.1975 (56)	2.1975 (56)	2.2215 (60)	2.1975 (56)	2.1975 (56)	1.7595 (44)	2.2215 (60)	2.1975 (56)	2.2215 (60)	2.0814	0.1907	20.7594	0.0744
+1	-1	+1	1.9240 (06)	2.0590 (10)	2.6765 (18)	1.4830 (26)	1.6350 (35)	1.8130 (46)	1.8130 (46)	2.0075 (55)	2.0075 (55)	2.6570 (58)	2.0075 (55)	2.0075 (55)	1.8130 (46)	2.6570 (58)	2.0075 (55)	2.6570 (58)	2.0319	0.4352	13.3836	0.1904
+1	+1	-1	1.9150 (05)	1.9670 (13)	2.5730 (21)	1.9340 (25)	2.5500 (36)	1.4030 (41)	1.4030 (41)	1.7770 (50)	1.7770 (50)	2.6600 (57)	1.7770 (50)	1.7770 (50)	1.4030 (41)	2.6600 (57)	1.7770 (50)	2.6600 (57)	2.0975	0.4487	13.3956	0.2256
+1	+1	+1	1.8260 (02)	2.2550 (14)	2.4680 (17)	1.7320 (31)	2.1190 (39)	1.9930 (42)	1.9930 (42)	2.2340 (54)	2.2340 (54)	2.6950 (64)	2.2340 (54)	2.2340 (54)	1.9930 (42)	2.6950 (64)	2.2340 (54)	2.6950 (64)	2.1656	0.3208	16.5866	0.1745

Notes: (a) Factor A: SPI adjuster screw length; Factor B: Presser foot pressure; Factor C: Feed-dog height; D: Fabric type; E: Presser foot condition; F: Handling techniques (for actual levels for each factor, see Table 5.8 in section 5.5.1).
(b) Figures in parenthesis show the run order: the SNR was calculated using eq. 7.1; an alternative SNR based on the Mean Square Deviation (MSD), $SNR_{MSD} = -10\log_{10}(MSD)$, provide similar Minitab outputs.
(c) The reader is reminded (details in section 5.4.1) that the researcher had to use a Vernier calliper (calibrated in inches) to take back-coverage measurements using a template (Gamage's improved measurement gauge) to improve the precision of the measurement system. This is why the response (Y) values are shown up to 4 decimal places.

In keeping with Taguchi's two step optimisation strategy (details in section 3.4.1) *which is also consistent with conventional DoE* (Montgomery, 2013), the variability of the process was reduced first by identifying and manipulating the factors that have a significant effect on the SNR (the goal was to look for significant factors and set their settings, to result in a higher SNR). Thereafter (the second step), an attempt was made to look for a so called "adjustment factor" to manipulate that factor to adjust the process mean to the target value. An adjustment factor is a factor that has a negligible effect on the SNR (hence process variability) but has a sizable effect on the process mean (Roy, 2010; Taguchi et al., 2005; Wu & Chyu, 2002). Manipulating an adjustment factor, by definition, brings the process mean to the target without compromising the already minimised variability (Taguchi et al., 2005).

In order to answer the research question RQ3, Taguchi's RPD approach was compared (and contrasted) with the conventional DoE approach (see section 7.4 for the discussion); this enabled the researcher to identify the statistical and operational merits and demerits of Taguchi methods, relative to a baseline DoE method. Consequently, the following two competing statistical methods were considered. The same data (Table 7.2) were used in both methods.

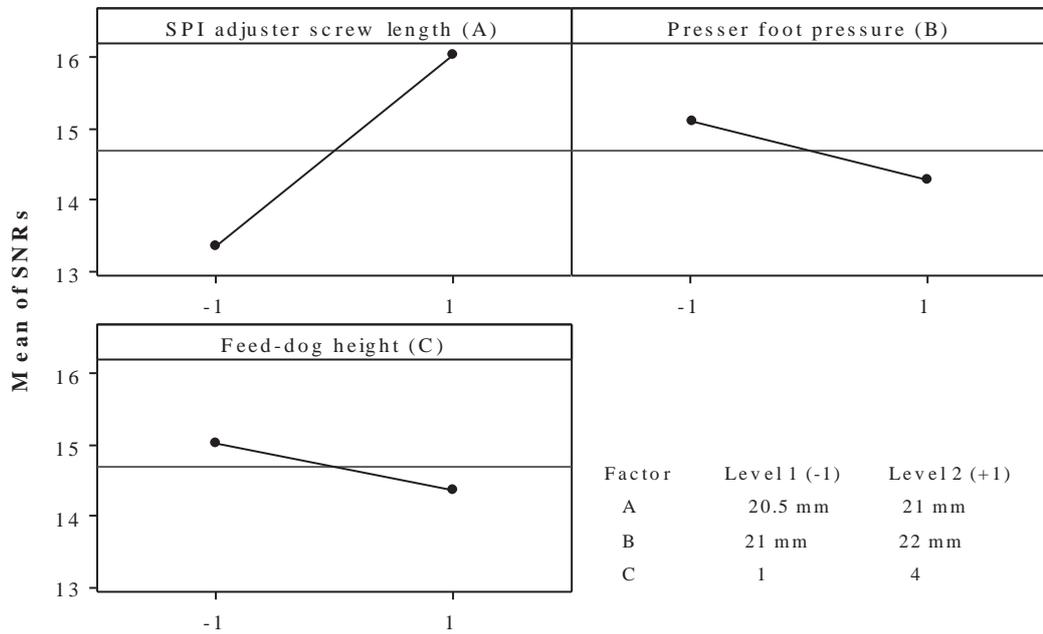
Method I – Optimisation using the crossed-array approach coupled with the statistical tools prescribed by Taguchi; in other words, optimisation using Taguchi methods.

Method II – Optimisation using the combined-array approach, where the inner array and the outer array are combined and the data are analysed using conventional DoE techniques (the baseline DoE method for setting design parameters to achieve robustness). In the DoE literature this method of setting design parameters is known as the "response surface approach to RPD" (Khuri & Mukhopadhyay, 2010, p. 136).

7.3.1. Crossed-Array Approach/Taguchi Methods (Method I)

This section covers the standard analysis prescribed in Taguchi methods. Graphical plots play an important role in Taguchi methods in identifying the robust parameter (control factor) settings (Antony & Antony, 2001). The main effects plot of SNR was used to identify factor effects and their settings to minimise the variability of the

response (Y), while the main effects plot of Y (the measured response) was used to identify the factor effects on the expected value of Y (i.e. the process mean).



Signal-to-noise: Nominal is best ($10 \cdot \log_{10}(\bar{Y}^2/s^2)$)

Figure 7.5: The main effect plots of the SNR

Figure 7.5 shows the main effects plot of the SNR. Figure 7.5 suggests that Factor A is a factor that has a practically significant effect on the SNR while factors B and C are factors that have a lesser effect on the SNR. As such, factors B and C become good candidates for mean adjustment if they show a practically significant effect on the expected value of Y . In any case, Figure 7.5 shows that the SNR is maximised when Factor A (length of the SPI adjustment screw) is at the high setting, Factor B (presser foot pressure) is set at the low setting and Factor C (feed-dog height) is also set at the low setting. Data in Table 7.2 shows that these settings provide a considerably lesser MSD relative to the other settings. Since the MSD represents the deviation of the observations (on average) from the target value (1.875") and since loss to society (according to Taguchi's Quality Philosophy) is quadratically proportional to this deviation (i.e. MSD), the results imply that it prudent not to make further adjustments to the factor settings to reduce variation.

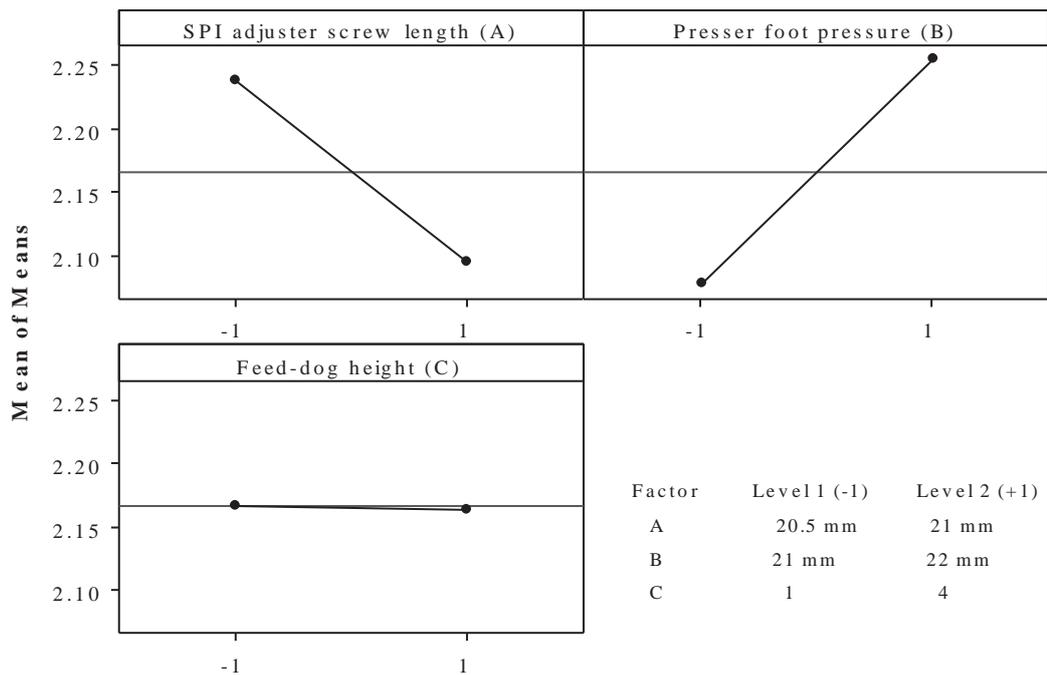


Figure 7.6: The main effect plots of the back-coverage

Figure 7.6 shows the main effect plots of Y (back-coverage measurement). This figure shows that both factors A and B have a practically significant effect on the expected value (average) of the back-coverage measurement while factor C has no significant effect. Since factor A was found to have a practically significant effect on the SNR (and hence the process variability), it becomes clear that factor A should not be manipulated (it has to remain fixed at the high setting), should the engineers want to adjust the mean. Thus Factor B becomes the candidate for the adjustment factor (if required) by default.

The recommendation that was made to the QI team was as follows:

Set Factor A (length of the SPI adjustment screw) at the high setting, Factor B (presser foot pressure) at the low setting and Factor C (feed-dog height) at the low setting; adjust the presser foot pressure (Factor B) to bring the mean to the target, if necessary; conduct confirmation runs to verify the result.

Using the MSD values shown in Table 7.2 it was also shown to the QI team that mean adjustment by manipulating the adjustment factor may result in a higher loss (due to a

higher MSD) and hence mean adjustment should be undertaken cautiously. It was also reminded to the QI team that variation can occur due to causes outside the process (sewing) being studied—in particular, the cutting process (see section 5.2.3 for details),⁵¹ and that this experiment may not be the most effective experiment to minimise the variation.

7.3.1.1. The Confirmation Runs

Confirmation of the solution by way of conducting a number of replicated runs (the replicated runs represent the variability due to the noise profile) at the supposedly optimum setting (as discussed in the previous section, factor A at high setting (1), factor B at low setting (-1) and factor C at low (-1) setting) is an integral part in any statistically designed optimisation experiment (Azadeh et al., 2012; Montgomery, 2013). A confirmation runs mark the final stage of the Taguchi’s RPD (Ross, 1996). Table 7.3 shows the sixteen back-coverage measurements taken during the confirmation runs.

Table 7.3: Back-Coverage Measurements Obtained During the Confirmation Runs

Back-Coverage Measurements for the Noise Profile Consisting of Factors D, E and F									
(Inches)									
D		-1	-1	+1	-1	+1	-1	+1	+1
E		+1	-1	-1	-1	-1	+1	+1	+1
F		+1	+1	+1	-1	-1	-1	+1	-1
Optimum Settings	A = +1	1.6595	2.1304	1.8791	2.0651	1.9941	1.7223	1.6687	2.1171
	B = -1	1.7391	2.0755	1.9525	2.1185	2.0841	1.7146	1.6477	2.0469
	C = -1								

⁵¹ It can be argued that mean adjustment could be made by making a minor adjustment to the back-coverage dimension of the marker; see Figure 5.8b in section 5.3.3.

7.3.1.2. The Financial Impact Assessment

Table 7.4 shows four useful process performance measures before and after the QI experiments.⁵²

Table 7.4: Comparison of Performance Measures Before and After the Experiments

Performance Measure	Data Analysis	Confirmation Runs	Before QI Experiments (Status Quo)
Process Average	2.0814	1.9130	1.9085
Process Standard Deviation	0.1907	0.1894	0.2373
MSD	0.0744	0.0351	0.0497
SNR	20.7594	20.0872	18.7085
Notes: (a) ‘Data Analysis’ means analysis of the experimental data (Table 7.2) using the main effect plots shown in Figure 7.5 and Figure 7.6. (b) The performance measures before the QI experiments (baseline information) are based on the data obtained for process stability and capability analysis (section 7.2.2).			

The confirmation run results show that the results obtained from the experiment (Method I) are close to the confirmation run results. The optimum factor settings obtained from the experiment (and confirmed by the confirmation runs) gave a more robust setting, and hence an improved product, relative to the status quo (situation prior to the QI experiment). Based on the traditional “goal post” approach of rejecting products outside the specification limits ($USL = 2.125$ and $LCL = 1.625$), the process before QI is expected to cause (under the assumption of normally distributed data) a rejection rate of 296,905 pieces of garments for every one million garments inspected (see Figure 7.4), while the process after QI is expected to cause (under the conditions of normality assuming an estimated process mean of 1.9130 and a standard deviation of 0.1894, as per the confirmation run results shown in Table 7.4) only a rejection rate of 195,500 pieces (approx.) of garments for every one million garments inspected. This equates to avoiding sending 101,405 pieces of additional garments (approx.) for rework/scrap for every one million pieces of garments inspected. If the process can be

⁵² It is important to note that the confirmation runs were run 12 days after the experiment due to practical reasons (e.g. completion of the data analysis from the experiment and discussion of the results with the QI team and the researcher’s supervisors (via video conferencing). The specimens for the confirmation runs came from the actual production run (batch production was in operation at the time) while the specimens for the experiment came from a training run where the pieces of fabric were cut for a training run by the cutting department. This could cause an unaccounted variability in the analysis.

centred to the target value of 1.875", maintaining the same process variability (the standard deviation of 0.1894), it can be shown that the staff could avoid sending 110,205 pieces of additional garments (approx.) for rework/scrap for every one million pieces of garments inspected.⁵³ For a Lean organisation, avoiding this amount of waste (based on the goal post notion of quality control course) is an attractive proposition.

The high SNR values (and low MSD values) in the confirmation runs relative to the corresponding values for the status quo, also indicate the impact of the improvement in statistical terms, in a different way (the quadratic loss function notion, as promulgated by Taguchi). This impact was translated to a financial impact using certain assumptions (see Appendix F for details).

7.3.2. Combined-Array Approach/Conventional DoE Approach (Method II)

Combined-array, as the terms suggests, combines experimental factors and noise factors into one array (each column the array represents a factor) and each factor is treated as an independent variable for analysing the data. The dependent variable is the back-coverage measurement. The combined-array is shown in Appendix G.

Figure 7.7 shows the main effects plot of the back-coverage measurement. By definition the main effects plots for the control factors will be identical to those obtained in method I (Taguchi methods) because the average \bar{Y} (back-coverage) values for the -1 and +1 settings remain the same (see Figure 7.6). Figure 7.7 shows that factors A, B, and D are more important (influential on \bar{Y}) than factors C, E and F. In addition, the figure shows that fabric type is the dominant noise factor (source) but the handling technique as a noise factor also has some effect on the back-coverage.

⁵³ These figures can be obtained either using probability values (probability of an observation lying outside the lower and upper specification limits, given the mean and the standard deviation of the probability distribution) given by an online probability calculator or by using standard normal tables.

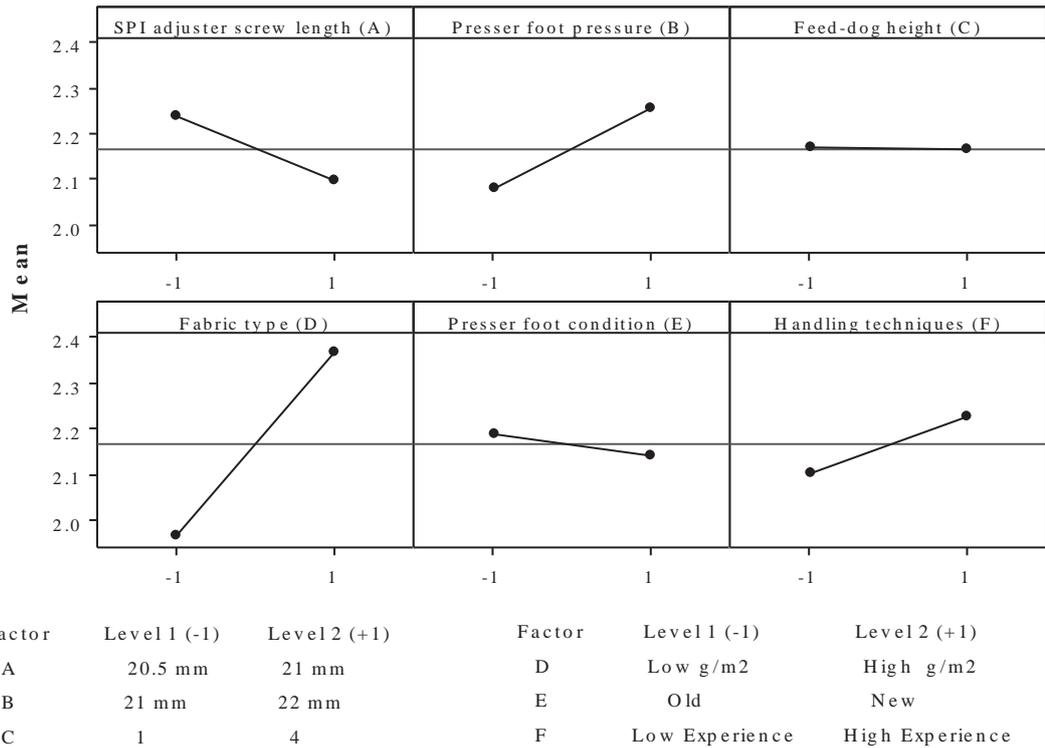


Figure 7.7: Main effect plots of the three control factors and the three noise factors

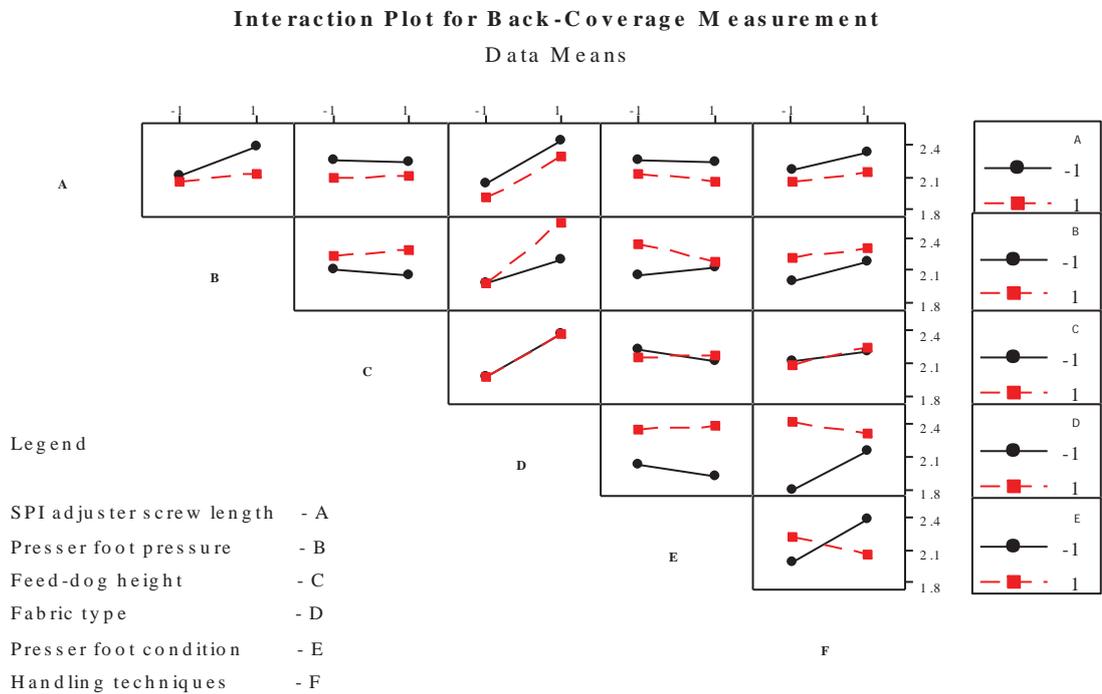
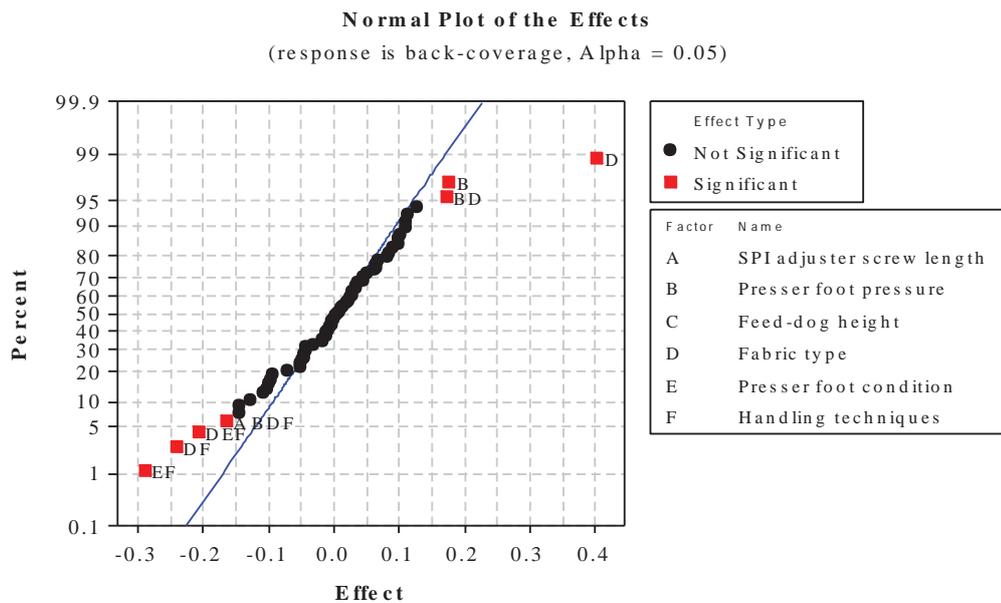


Figure 7.8: Two way interaction plots between all the factors

Figure 7.8 shows the two-way interaction plots involving all six factors (D, E and F are noise factors). A two way interaction between two control factors as well as a two way

interaction between a control factor and a noise factor have an effect on the robust parameter setting (Montgomery, 2013). Interactions between noise factors are interesting. For example, the DF interaction shows that a highly skilled operator ($F = +1$) can cope with fabric type (thick or thin) better than an unskilled operator ($F = -1$). However, in real operation, tightening the tolerance to reduce the variability of noise factors, for example, maintaining highly skilled operators all the time, is cost prohibitive.⁵⁴ As such, from a process robustisation perspective, interactions between noise factors are not useful. Therefore Figure 7.8 shows that the two-way interactions AB, BD and BE are the candidates that warrant further examination.

Normal probability plot (NPP) is a very useful initial approach to identify the significant terms when it is not possible to estimate the Mean Square Error (MSE) for the analysis of variance (Montgomery, 2013).⁵⁵



Lenth's PSE = 0.0733734

Figure 7.9: Normal probability plot of effects for the default model

⁵⁴ A large proportion of females engaging in factory type jobs (this is more so in the apparel industry) in the Sri Lankan labour force quit their job when they get married; they seldom re-enter to the workforce; this is part of the value system (culture) in the Sri Lankan society; this basically means that there will always be young faces (less experienced seam stresses) in the workforce.

⁵⁵ In Method II, since all 6 factors remain experimental factors the experiment boils down to an unreplicated 26 factorial design. If one attempts to include all possible terms (i.e. all 26-1 terms possible) in the ANOVA, the MSE cannot be estimated as both the error and the degrees of freedom of error become zero.

Figure 7.9 shows the NPP of the default model (i.e. the model containing all the possible terms involving factors and their interactions). The plot shows that at 5% level of significance, control factor B and noise factor D as well as the control to noise interaction BD are useful for process robustisation; the significant interactions between the noise factors (EF, DF, DEF) are interesting, but from a process robustisation perspective, they are unimportant because one cannot do much about these interactions as noise factors by definition are uncontrollable under normal process conditions.⁵⁶

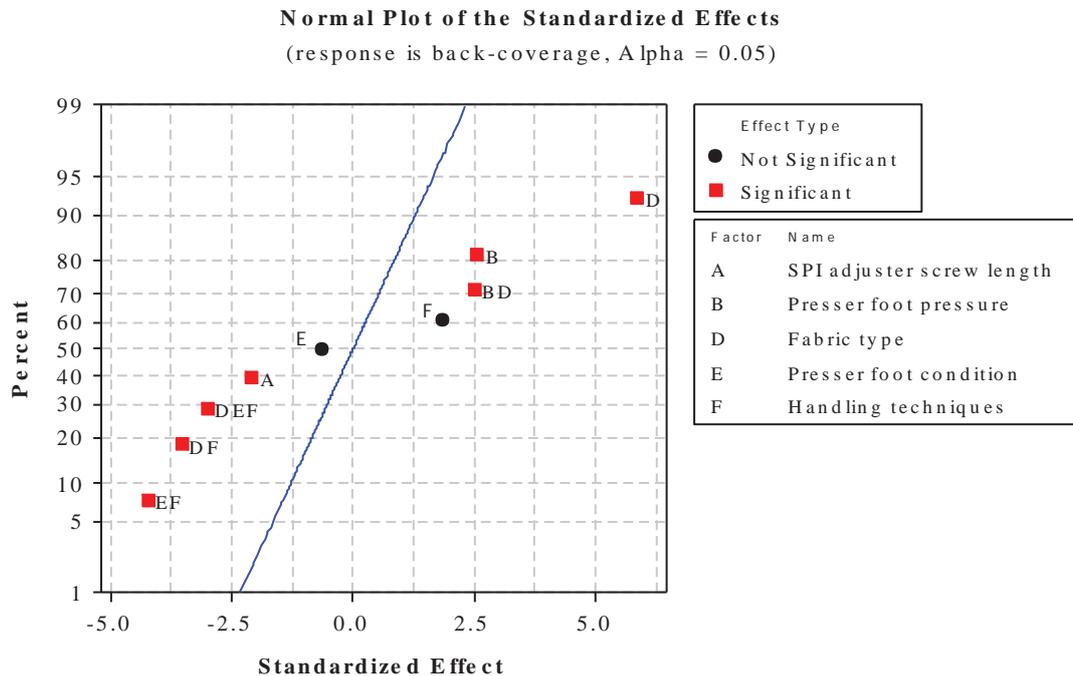


Figure 7.10: Normal probability plot of effects for the reduced model

Figure 7.10 shows the NPP of effects for the reduced model; this model includes all the main effects and significant interactions found previously (Figure 7.9). Figure 7.10 shows that all but terms E and F in the reduced model are significant at 5% significance level. Among the significant terms, Factor A returned a p value of 0.041 from the analysis of variance (ANOVA), implying that Factor A is just significant.

The ANOVA was subsequently conducted excluding the three way interaction term DEF; it was assumed that an interaction involving three noise factors is unlikely to be

⁵⁶ For an example one cannot change the fabric type in the middle of a production run!

active, based on factor sparsity (Kunert, 1997). The results of the ANOVA for this final model are shown in Figure 7.11.

```

Factorial Fit: Back-coverage versus A: SPI adjuster screw length; B:
Presser foot pressure; D: Fabric type; E: Presser foot condition; F:
Handling techniques.

Estimated Effects and Coefficients for Y (coded units)

Term      Effect      Coef  SE Coef      T      P
Constant  2.1660  0.03683  58.80  0.000
A         -0.1438 -0.0719  0.03683  -1.95  0.056
B          0.1770  0.0885  0.03683   2.40  0.020
D          0.4043  0.2022  0.03683   5.49  0.000
E         -0.0444 -0.0222  0.03683  -0.60  0.549
F          0.1273  0.0636  0.03683   1.73  0.090
B*D       0.1725  0.0863  0.03683   2.34  0.023
D*F      -0.2426 -0.1213  0.03683  -3.29  0.002
E*F      -0.2903 -0.1452  0.03683  -3.94  0.000

S = 0.294680    PRESS = 6.46693
R-Sq = 57.66%   R-Sq(pred) = 42.67%   R-Sq(adj) = 51.50%

Analysis of Variance for Y (coded units)

Source          DF   Seq SS   Adj SS   Adj MS   F      P
Main Effects    5    3.7388  3.73878  0.74776  8.61  0.000
  A              1    0.3308  0.33081  0.33081  3.81  0.056
  B              1    0.5015  0.50149  0.50149  5.78  0.020
  D              1    2.6156  2.61562  2.61562 30.12  0.000
  E              1    0.0316  0.03161  0.03161  0.36  0.549
  F              1    0.2592  0.25925  0.25925  2.99  0.090
2-Way Interactions  3    2.7661  2.76605  0.92202 10.62  0.000
  B*D            1    0.4762  0.47615  0.47615  5.48  0.023
  D*F            1    0.9413  0.94131  0.94131 10.84  0.002
  E*F            1    1.3486  1.34859  1.34859 15.53  0.000
Residual Error  55    4.7760  4.77599  0.08684
  Lack of Fit    23    2.2295  2.22949  0.09693  1.22  0.298
  Pure Error     32    2.5465  2.54650  0.07958
Total           63   11.2808

```

Figure 7.11: Estimated model parameters and the ANOVA results for the final model

Figure 7.11 shows that when the 3-way interaction terms DEF is removed, Factor A becomes (just) insignificant ($p = 0.056$) at 5% level. However, Factor A was retained for the response function (regression equation for back-coverage Y), based on the previous evidence (Figure 7.10). More importantly, the ANOVA shows that the lack-of-fit component is insignificant at 5% significance level, justifying the reduced model.⁵⁷ However, Figure 7.11 shows that the model has low R^2 values, which implies that there

⁵⁷ This basically means that the variation due to the 23 terms removed from the default model is small (as an F ratio) relative to pure error, suggesting that removals of these terms are justified.

is a substantial amount of unexplained variation associated with the model, in spite of accounting for three noise factors.

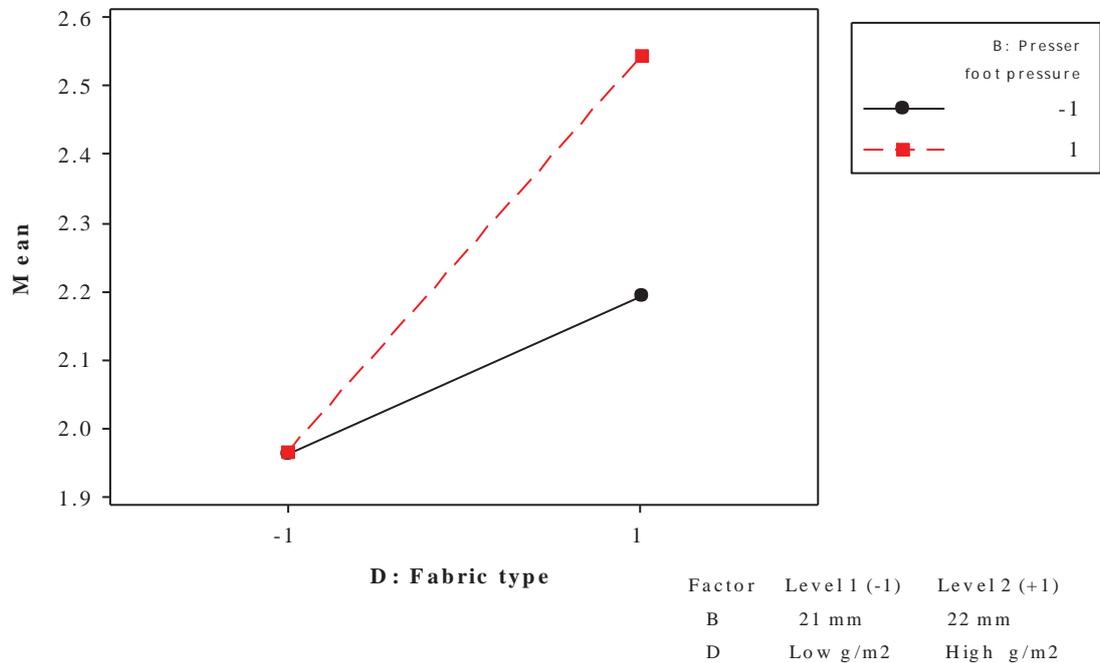


Figure 7.12: Interaction plot between noise factor (D) and control factor (B)

Figure 7.12 shows the only statistically significant control to noise factor two way interaction, being the interaction between a control factor B (presser foot pressure) and a noise factor D (fabric type). If not for this interaction, there would be no robust setting (i.e. an optimum control factor setting) within a RPD framework (this is clear from eq. 7.5 show later also). The interaction plot shows that the variability transmitted from the variation of weight of the fabric (fabric type) will be minimised when the presser foot pressure (factor B) is set at the low (-1) level.

7.3.3. The Response Function for the Back-Coverage

The response function (model) in coded units, based on the parameter estimates given in Figure 7.11, is shown in eq. 7.2.

$$\hat{Y} = 2.166 - 0.0719 A + 0.0885 B + 0.2022 D - 0.0222 E + 0.0636 F + 0.0863BD - 0.1213 DF - 0.1452 EF + \varepsilon \quad (7.2)$$

In eq. 7.2 above, ε is the random disturbance term (assumed to be normally distributed) with a mean 0 and a variance of σ^2 . It is important to note that eq. 7.2 above is an estimate of the population model (hence all the coefficients in the equation are mere estimates of the true coefficients, which are unknown). Figure 7.13 shows the pack of four graphs that Minitab produced for the residuals of the final model (eq. 7.2).

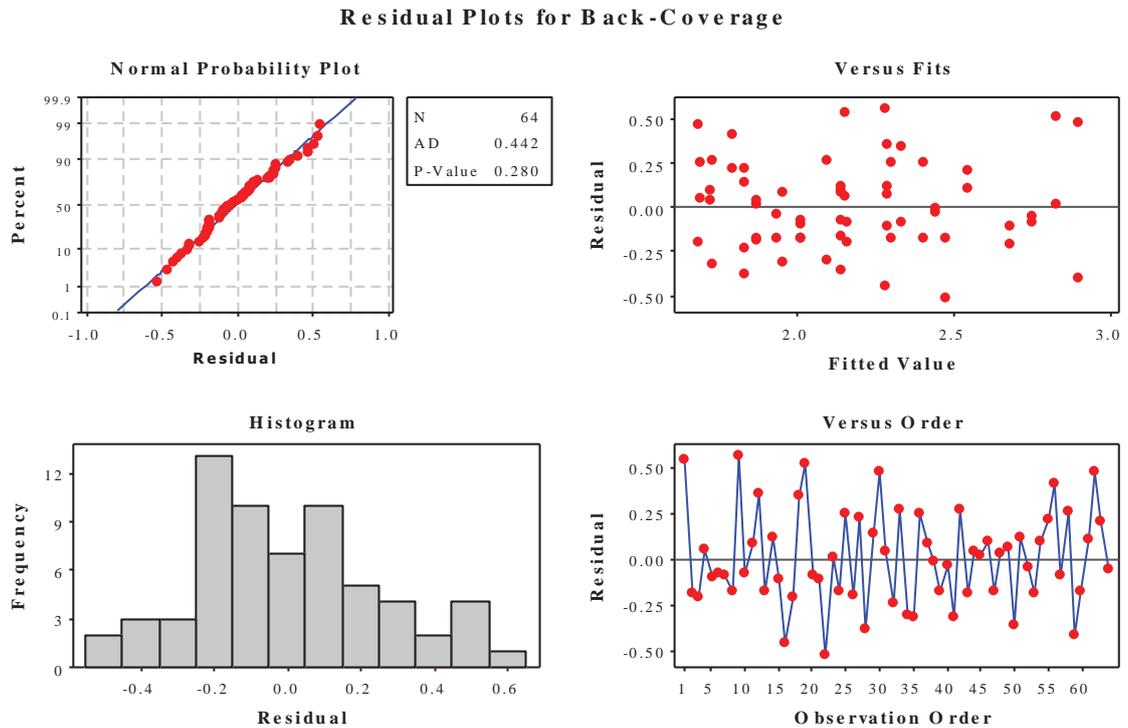


Figure 7.13: Residual plots for the final model (eq. 7.2)

The normal probability plot graph shows that the residuals are normally distributed; the histogram shows that the residuals are not skewed; the versus fits graph does not show serious issues on homoscedasticity, while the versus order graph does not show evidence of serial autocorrelation. These plots therefore imply “model adequacy” (Montgomery, 2009). Consequently, while low R^2 of the model was a concern, the researcher went on to use eq. 7.2 to derive subsequent equations.

In the actual process, the noise factors (as well as the random disturbance term) are assumed to be random variables whose means are zero.⁵⁸ Therefore the mean value or

⁵⁸ The average value of a noise factor = 0 is justifiable because it is reasonable to assume that there will be as many -1 settings of a factor as there are +1 settings, making the average = 0.

the expected value (process centre) of response Y (back-coverage), when the process is subjected to the noise is given by:

$$\bar{E}(Y) = 2.166 - 0.0719 A + 0.0885 B \quad (7.3)$$

Now, calculating the conditional variance of Y from eq. 7.2, given that all terms but 0.2022 D and 0.0863 BD (since B is fixed in the real operation, both 0.2022 D and 0.0863 BD are dependent on D only) are independent, we get:

$$\overline{\text{Var}}_{\text{var}}(Y) = (0.0863 B + 0.2022)^2 \sigma_D^2 + 0.0222^2 \sigma_E^2 + 0.0636^2 \sigma_F^2 + 0.1213^2 \sigma_D^2 \sigma_F^2 + 0.1452^2 \sigma_E^2 \sigma_F^2 + \sigma^2 \quad (7.4)$$

σ^2 is the unexplained variance of the (true/population) model.

Note: Conditional variance of Y (denoted $\overline{\text{Var}}_{\text{var}}(Y)$) means the variance of Y , given that the control factors will be at fixed levels, when the process is actually being subjected to noise. For ease of communication, the conditional variance of Y will be referred to as variance in this thesis from here onwards. Assuming that each noise factor has a unit variance⁵⁹ (i.e. $\sigma_D^2 = \sigma_E^2 = \sigma_F^2 = 1$), from eq. 7.4 we get:

$$\overline{\text{Var}}_{\text{var}}(Y) = [0.0863^2 (B + 2.34)^2 + 0.04030 + \sigma^2] \quad (7.5)$$

From eq. 7.5, the transmitted variability is minimised when: $d\{\overline{\text{Var}}_{\text{var}}(Y)\}/dB = 0$. This results in a process variability of $(0.04030 + \sigma^2)$ at Factor $B = -2.34$ coded units.

Even though σ^2 of a regression model is never known, it was assumed to be equal to the mean square error s^2 (Montgomery, 2013) based on sample data, which is 0.08684 (Figure 7.11).⁶⁰ Thus, at the robust setting (based on the regression analysis), the process is estimated to be showing a variance of 0.12714 (being $0.04030 + 0.08684$). Conversely, the process is estimated to be showing a standard deviation of 0.35657, at the robust setting. This estimated value is much higher than the process standard deviation of 0.2373 (Table 7.4) before the QI experiment. This discrepancy occurs probably because of the assumption that s^2 is a reasonable proxy for σ^2 (see footnote #

⁵⁹ This again can be justified (at least in a test situation) because -1 and +1 points are unit distance from the mean.

⁶⁰ Note that s^2 is a crude estimate of σ^2 . Typically, the estimate for σ^2 is calculated from “pure error” through replicated centre point runs (Montgomery, 2013). Centre points were not considered in the researcher’s experiment to keep things simple.

60). It is argued that because the parent model shown in eq. 7.2 is shown to possess model adequacy (based on the residual plots), the response functions given in eq. 7.4 and 7.5 are still informative, although like in any robust design, the final solution needs to be confirmed using confirmation runs.

Figure 7.14 (derived from eq. 7.5) shows how the variance of Y changes with the setting of Factor B. The transmitted variability (due to fabric variation) is minimised when the spring of the presser foot pressure controller (B) height is set at -2.34 coded units (19.33 mm), based on extrapolation; this (adjusting the screw to 19.33 mm) is a feasible machine setting.

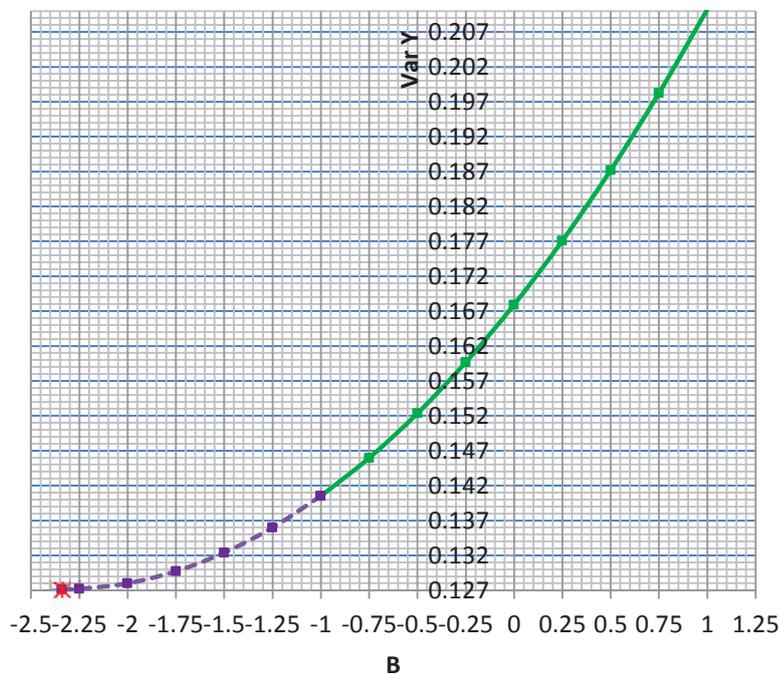


Figure 7.14: The variance of Y vs B in coded units

The contour plots derived from eq. 7.2 are shown in Figure 7.15 and Figure 7.16. The difference between the two figures is that Figure 7.15 only covers the normal range (-1 and +1) in which the factors were actually manipulated while Figure 7.16 covers the extended range based on extrapolation. Both plots are derived from eq. 7.3 shown above.

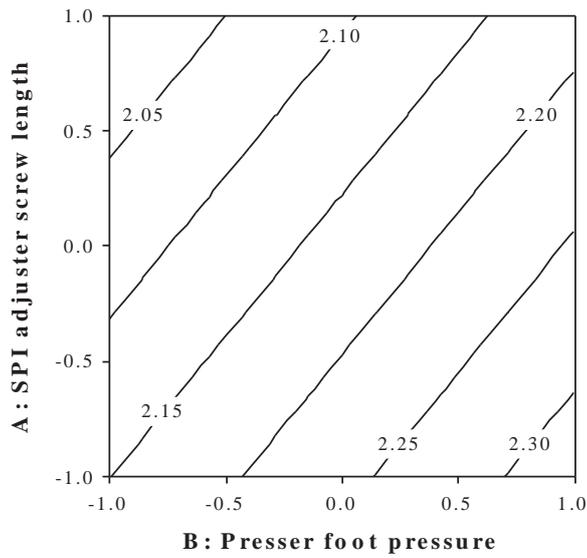


Figure 7.15: Contour plot of average back-coverage vs A, B [coding system: -1, +1]

Given that the target value of Y is 1.875", and Factor B has to be set at -2.34 coded units to minimise the variability, Figure 7.16 shows that the target value can be achieved when Factor A (SPI adjuster screw length) is increased slightly above the +1 setting (1.17 to be exact).

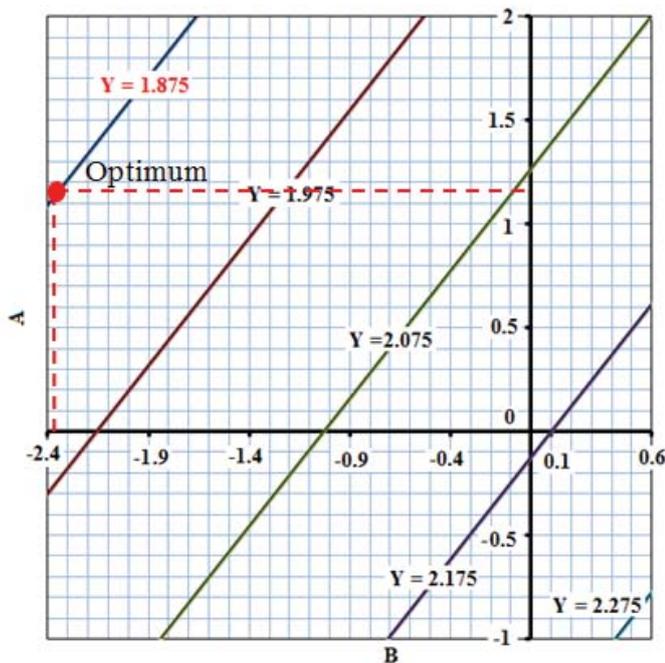


Figure 7.16: Contour plot of average back-coverage vs A, B based on extrapolation

7.4. DISCUSSION: STATISTICAL AND OPERATIONAL MERITS/ DEMERITS OF TAGUCHI METHODS

The framework used by the researcher for discussing the results (section 7.3) is depicted in Figure 7.17.

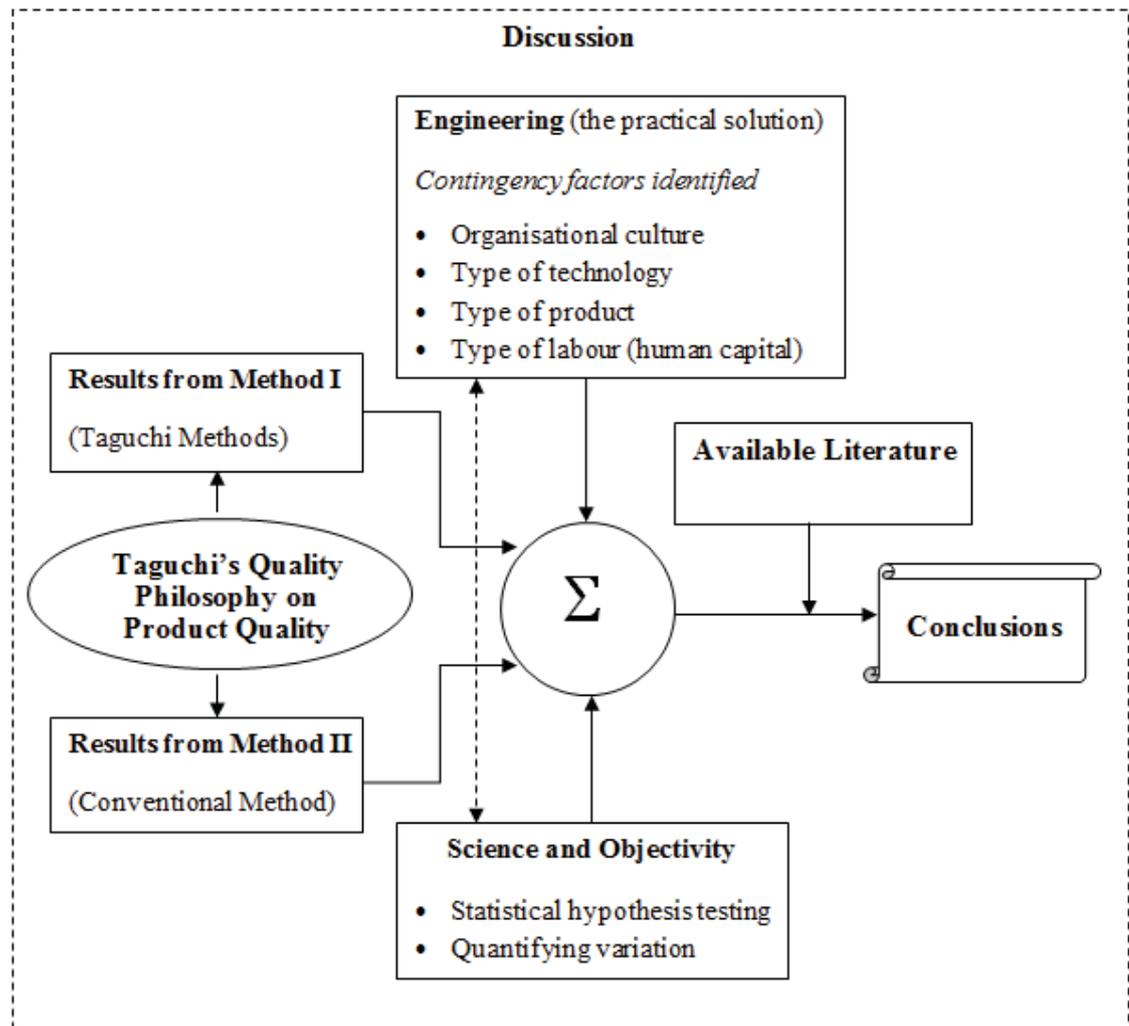


Figure 7.17: The framework for discussion

The researcher's discussion framework (Figure 7.17) basically represents the following facts:

- Both data analytic methods on robust designs (the "Taguchi methods", which involve such statistical tools as crossed-arrays, SNRs etc. and the conventional DoE methods, which are strongly shaped by characterisation of the phenomenon

being studied using response functions) share a same philosophy on building quality in the product design.

- The results of the fieldwork need to be interpreted in the light of several contingency factors, which an engineer would call “practical considerations”.
- The results of the fieldwork need to be assessed against the norms of sciences and objectivity; that is, the discussion should evolve around the results from the experiment and other fieldwork conducted by the researcher.
- The results of the fieldwork need to be interpreted and discussed in the light of the extant literature (this goes without saying!).

Taguchi’s Quality Philosophy holds that products need to be designed to be robust against noise. In other words, the functional characteristic (in this study, the ‘back-coverage’ measurement of the garment being studied, for example) of a well-designed product should show low variability (whilst in production or in use) around its target value. Thankfully, this proposition has been entertained by practitioners and scholars belonging to both camps: the ones in the “Taguchi camp” (e.g. Antony et al., 2001; Gunter, 1987; Mayer & Benjamin, 1992; Roy, 2010; Taguchi et al., 2005) and the ones in the “anti-Taguchi camp”, who rely on conventional DoE methodologies to achieve a robust design (e.g. Box et al., 1988; Montgomery, 2009). In addition, both camps take Taguchi’s two-step optimisation procedure on board: minimising the variability of the product’s functional characteristic by identifying the important control factors and manipulating them (step 1) and bringing the process average close to the target, without compromising process variability by identifying and manipulating an adjustment factor (Box, 1988; Park et al., 2006; Taguchi et al., 2005; Taguchi, Jugulum, & Taguchi, 2004).

The conventional DoE approach⁶¹ relies heavily on statistical hypothesis testing (e.g. decision to include a term in the response function depends on its *p* value) and process characterisation using response functions that use least squares methods to estimate

⁶¹ It is important to note that conventional DoE methods involve a family of process optimisation methods: factorial designs (full or fractional factorial), response surface methodologies, evolutionary operations and non-orthogonal factorial designs (Lekivetz & Tang, 2011; Pearce, 1963) All of these methods have a place in making products robust against environmental noise. This study considers (under Method II) the response surface approach to RPD only.

model parameters (Khuri & Mukhopadhyay, 2010; Montgomery, 2013). In this study, the researcher used two key response functions: one function was used to model the process variability (eq. 7.5) and the other function was used to model the process average (eq. 7.3), using the primary regression equation shown in eq. 7.2. In spite of the QI team being able to identify three noise factors, the primary regression equation (after allowing for variability due to the control factors and noise factors) could only explain 57.66% of the total variability (Figure 7.11). This shows the technical challenge in deriving well-fitting empirical models (such models are an integral part in conventional DoE methods) to predict and explain process outcomes (back coverage variability) such as the one the researcher studied.

The reader will note that the conventional DoE method (the response surface alternative) provided more information to the analyst about how the process works and how the process should be operated. Whereas the analyst based on Taguchi methods (method I) was only select the optimum combination of control factor settings from the levels chosen by the analyst (-1 and +1 settings in the case of study) (Cabrera-Rios, Mount-Campbell, & Irani, 2002; Chen, Kumar, & Glowacki, 2009; Myers et al., 1992), the conventional DoE method (method II) was able to provide an optimum combination of control factor settings outside the chosen settings. Thus in theory, the latter method provided a more optimum setting (via differential calculus) than the former due to the response functions derived. However, both methods basically provided the same detections to the QI team: keep Factor A as high as possible, keep Factor B as low as possible, and Factor C is not strongly active.

The Taguchi methods informed the experimenter that Factor A should be manipulated to reduce variation (step 1) and Factor B should be manipulated to adjust the process mean (step 2) while the conventional method informed the experimenter that Factor B should be manipulated to reduce process variation (step 1) and Factor A should be manipulated to adjust the process mean (step 2). The researcher notes that some past studies (e.g. Bisgaard & Sutherland, 2003; Box et al., 1988; Montgomery, 1999) that re-analysed data from Taguchi-style experiments have come-up with similar mystifying results. Perhaps, there might not be a serious issue here because Taguchi methods use the SNR in the first step, which in actual fact, attempts to reduce variability (a high SNR means a low MSD) whilst bringing the process centre as close as possible to the target (Roy, 2010; Wu & Chyu, 2002). Hence the first step in Taguchi methods in actual

fact may leave the second step to provide only a minor adjustment (if required). It could also be possible that, perhaps, in spite of their best efforts, the researcher and the QI team were not able to fully understand the noise profile that caused the variability of the response (eq. 7.2 also suggests so). Taguchi methods rely on the *engineering knowledge* for being able to reproduce the actual noise profile that causes the variation (the noise factors and their levels) in the experiment (Gunter, 1987; Prasad, Mohan, Rao, Pati, & Sarma, 2005; Roy, 2010).⁶² A conventional DoE method relies on building process knowledge sequentially, using smaller experiments that aim to address one or few research questions at a time (e.g. at the early stage: what are the important factors? and at a later stage: what is the response function that represents the optimal response region?); stated alternatively, conventional methods take less risks by not relying on the engineering knowledge upfront (Box et al., 1988; Montgomery, 2013).

It could be argued that both methods provide some challenges in the apparel industry, in relation to manufacturing new products. Apparel manufacturing belongs to the fashion industry and in this industry products do have short life cycles (Barnes-Schuster, Bassok, & Anupindi, 2002; Bruce et al., 2004; Mostard, Teunter, & De Koster, 2011; Thomassey, 2010). Frequently changing/short product lifecycle product designs mean that it is difficult, if not impossible to build process knowledge sequentially as advocated in conventional DoE methods. On the same token, it may be challenging for the staff to build the full engineering knowledge about manufacturing a specific design (e.g. cutting and sewing) at the time of setting up an experiment to design a new product; the researcher's experience in designing an experiment to improve the sewing process of a new style of women's brief is a good example.

A demerit of Taguchi methods that is often cited in the literature by some statisticians (e.g. Box et al., 1988; Nair et al., 1992), is that Taguchi methods require large number of experimental runs. This became obvious in analysing the results. The two L8 orthogonal arrays used in method I (Taguchi methods) resulted in a combined-array representing an un-replicated full factorial design involving six factors (i.e. a 2^6 design involving 64 experimental runs) for method II (conventional DoE). It can be easily shown that taking a half fraction of this design (i.e. a 2^{6-1} fractional factorial design

⁶² In cases where this is difficult, the best an experimenter can do is to run several replicates in the hope that replications would represent the noise (in this case the outer array does not have labels for noise factors).

involving 32 runs) could have still produced similar response functions and hence similar conclusions on how to optimise the process. Taguchi was an engineer, and hence he was more concerned with presenting an experimental design and a data analytic procedure that is standardised and easily understood by an everyday technical person (engineer included!) (Gunter, 1987; Rowlands et al., 2000; Thamizhmanii, Saparudin, & Hasan, 2007). Taguchi methods are less concerned with statistical efficiency and hypothesis testing.

Now, the researcher will turn to the merits of Taguchi methods (method I), giving considerations to a number of contingency factors that she identified (Figure 7.17). It must be mentioned that not all of the contingency factors are mutually exclusive.

7.4.1. Organisational Culture

The researcher observed that the Taguchi methods (method I) were in line with the culture of the organisation (essentially Lean) which require building knowledge through teamwork, respect for people, tool driven problem solving, and work standardisation. In particular, the researcher observed that the staff viewed Taguchi methods to be very transparent (they had to interpret very simple graphical plots) and intrinsically motivating as the method promoted teamwork, use of process knowledge to draw out control factors and noise factors capitalised on and group synergies. With regard to group synergies, Taguchi methods provided a good opportunity for mechanics and machine operators to appreciate that there is a way for both groups to work in harmony to improve the sewing outcomes; as mentioned in the next chapter (section 8.2.1.4) these two groups sometimes blame each other when things go wrong. The standardised nature of Taguchi methods meant that it was easy for the staff to figure out which two combinations of orthogonal arrays fit their experiment, given the number of control factors and noise factors involved in their experiment. On the same token, it was easy for them to remember that the response performance metric in Taguchi methods will always be the SNR, which can be computed very easily, given their optimisation objective.

The conventional method (method II), more technically precisely the response surface approach to RPD, was not well received by the technical staff and their superiors; more importantly, the researcher observed that the staff did not feel that they own the solution

provided by method II; one key staff member questioned why this method estimated a process standard deviation that was even higher than the one before the robustisation experiment! A complete answer to this question is very technical in nature (concepts such as pure error are beyond them) and the researcher was careful enough to give them simple answer: “*although sewing is a mechanically simple operation, it is difficult to accurately predict the variability of the process using a mathematical equation*”. Another one senior staff member quoted: “*the complex mathematics does tricks that we do not understand!*”. The staff opined that it is not their way of organising and doing things that make them rely on a statistician to save them! Another staff member (the quality manager) said:

Frontline workers are the most important people in our organisation and solutions for problems should evolve from them and not from a third party statistician doing number crunching for us; we want a simple and a practical solution. The method is OK, but not the second one.

It is interesting to note that some of the observations that the researcher made have some parallels with what Box observed nearly 30 years on the use to statistics for QI in Japan; Box observed that Japanese value tools and techniques that can be used by the masses as opposed to tools and techniques that can be used only by a handful of people to do fancy things (Box & Bisgaard, 1987).

7.4.2. Product Type, Technology, and Human Capital

Apparel manufacturing has always been labour intensive and it is hard to imagine that this is not going to be the case in the foreseeable future. In spite of the advancements in robotics, it is hard to imagine that a robot would be able to handle a piece of garment (which is very delicate by nature) in the same meticulous way a human being does. Even though apparel manufacturing is a low unit cost high volume industry, it requires different kind of labour than those required in many other low unit cost high volume industries (e.g. the dairy industry). The researcher observed that the apparel industry does not employ people who can handle the kind of mathematics and statistics required in method II; they prefer simpler (and standardised) approaches. In addition, it is documented in the literature that Taguchi style experiments are justifiable for low unit cost high volume industries as these can afford to run large experiments (Prasad et al.,

2005; Zhou, Ma, Tu, & Feng, 2013). For these reasons and the researcher's experience with her fieldwork, it is argued that Taguchi methods are more appropriate to the apparel industry. However, the researcher does not mean to support Dorian Shainin and Peter Shainin's notion that Taguchi methods are appropriate for "unsophisticated firms" (Shainin & Shainin, 1988).

7.4.3. Science and Objectivity

C. R. Rao, one of the most eminent statisticians living today, provides the following "logical equation" on which the "science of statistics" is founded (Rao, 1990):

"Uncertain Knowledge" + "Knowledge of Amount of Uncertainty" = "Certain Knowledge"

The researcher observes that Taguchi methods (method I) create knowledge about the amount of uncertainty by attempting to exploit the loss function by minimising the MSD (using the SNR) while the conventional DoE methods (method II) attempts to do the same using "least squares" regression methods. Therefore the researcher views both methods as statistically objective. Moreover, as explained at the beginning of section 7.4, both methods share some common elements. While both methods may have suffered from lack of full engineering knowledge about what causes variation/uncertainty of the back-coverage measurement of the product being studied, the researcher argues that Taguchi methods are practically more useful than conventional DoE methods, given the situational factors identified by her.

7.4.4. Adopting Taguchi's RPD Approach in a Lean Culture

Having reviewed the literature, and having conducted fieldwork, the researcher maintains that Taguchi's RPD approach is more acceptable to a Lean culture (see section 1.4, section 3.6.1) than a non-Lean culture. This is because Lean has many characteristics that favour the uptake of Taguchi's principles, practices, and tools and techniques, in relation to product quality improvement. These are as follows.

- The Conceptual Overlap: Sixth principle of Lean (see section 2.2.2: Lean Consumption) focuses on producing superior products at design stage (quality by design), taking into account the deterioration of

consumers' experience (due to poor product quality) when they use the product; Taguchi's RPD approach provides a proven methodology to accomplish quality by design.

- **Loss/Waste Concept:** A Lean production system is meant to add value to the customer and the organisation (in a broader sense, the supply chain) by eliminating waste and non-value adding activities, while Taguchi's approach is meant to add value to the customer and the organisation by minimising the overall loss to society by reducing variation in the product's functional performance. Both concepts look at creating value to the customer and the organisation by eliminating losses in the supply chain (it is acknowledged that unlike Lean, Taguchi's RPD approach is not meant to tackle all forms of losses/waste).
- **Teamwork (brainstorming):** both approaches heavily rely on team work and respect for people in solving problems; stated alternatively, both approaches insist on creating a problem solving culture, valuing the ideas of team members.
- **Standardised and Simple to use Methods:** Both approaches rely on standardised methods. In addition, both approaches value simplicity (unsophistication) to make product and process improvement an organisation-wide activity.

The researcher recommends that the above points need to be further verified through a comparative study involving Lean and Non-Lean manufacturing firms.

7.5. CHAPTER CONCLUSION

This chapter focused on answering the third research question by attempting to identify statistical and operational merits and demerits of using Taguchi methods (relative to conventional robust parameter design experimental methods) in a Lean apparel context, using field research. The results of the studies (the RPD experiments, the personal observations, and the outcomes of the discussions the researcher has had with the staff

of the case study factory) conducted by the researcher before and after the *quality improvement* (QI) experiments were presented and discussed in this chapter. In this chapter, the term “quality improvement” is used to mean reducing process variability around the target value to improve the robustness of the product and capability of the manufacturing process. The results on the studies prior to the experiments showed that the measurement gauge (as improved) was adequate for the task at hand (section 7.2.1) and that the process being studied (sewing) is stable but shows high variability, resulting in low process capability (section 7.2.2).

Both Taguchi methods (method I) and the conventional RPD method (method II) used to analyse the experimental data (section 7.3) provided similar directions to the QI team on parameter settings (set Factor A is at high level, Factor B is at low level, and Factor C is not strongly active). However there were some differences in the results produced by the two methods and these were discussed. The researcher would like to emphasise that the experiments (the main experiment covered in this chapter and the forerunner experiment covered in Appendix D) designed by the researcher might not have been the best experiments to reduce variability of back-coverage of the product being examined. The researcher has reported the results of the additional experiments to provide further evidence of the usability of Taguchi methods in Appendix H. The experiments were just means to an end—the means being to engage with Lean practitioners in the factory to solve manufacturing problems using robust parameter design methodologies; the end being answering the research question succinctly. Since the researcher was introducing robust parameter design methodologies to the staff in the case study factory for the first time, she had to be mindful of the fact that any extra complexity (e.g. to consider three level factors to account for nonlinearity) could come at the expense of the staff not fully understanding what is being done. In addition, the researcher assumed that there is negligible variation associated with the cutting process to keep the experiment and the data analysis simple.

Several contingency factors (the Lean culture of the organisation, type of product, type of technology, and type of labour) were identified by the researcher (section 7.4) to suggest that Taguchi methods (method I) are more suitable than the conventional method (method II) in a Lean apparel setting. In particular, it was hard to obtain the staff buy-in for method II, as they perceived that the statistician centred approach in method II is not in line with their Lean culture. Table 7.5 shows the summary of the

merits and demerits of the Taguchi methods relative to conventional robust parameter design methodologies, in a Lean apparel context, as identified by the researcher.

The operational and technical merits and demerits of Taguchi methods explained in Table 7.5 are the demerits and merits of conventional approach respectively. Taguchi methods are a highly standardised and easy to adopt (sophisticated statistical knowledge is not envisaged). More importantly, Taguchi methods rely on existing knowledge of team members, and therefore, teamwork and group synergies to design and develop experiments. Conventional approaches on the other hand rely on building knowledge from scratch by conducting a series of sequential experiments (as mentioned in section 3.3, different statistical techniques are required at each stage) by the experimenter. This means that conventional approaches require greater degree of statistical sophistication and are less team friendly.

Table 7.5: Merits and Demerits of the Taguchi Methods in the Context Studied

<i>Technical Merits</i>	<i>Technical Demerits</i>
Highly standardised	Require larger number of experimental runs
Easy to adopt and can apply with limited statistical knowledge	Does not build an empirical model (a regression equation) as such to predict or explain the process being studied
<i>Operational Merits</i>	<i>Operational Demerits</i>
Suitable for low unit cost high volume industries	Rely on prior engineering and technical knowledge to decide what factors are potentially important and at what levels they should be manipulated in setting up the experiment; prior knowledge may not be always be available in new product development
In line with the Lean culture	Only able to ‘pick the winner’; does not provide adequate information as to what happens to the process if the settings are moved within and outside the manipulated factor settings

Having justified Taguchi methods, the researcher goes on to answer her final research question (RQ4) in the next chapter.

CHAPTER 8

THE DRIVERS AND RESTRAINTS FOR THE APPLICATION OF TAGUCHI METHODS IN A MATURE LEAN APPAREL ENVIRONMENT AND RECOMMENDATIONS FOR CHANGE

“The sentence completes its signification only with its last term.”

—*Jacques Lacan*

*“To the man who only has a hammer, everything he encounters begins to look like a
nail”*

—*Abraham Maslow*

8.1. INTRODUCTION

Having shown that Taguchi’s Quality Philosophy on product quality (the primary element of Taguchi’s robust parameter design approach) meshes with Lean at theoretical level to achieve manufacturing process outcomes (Chapter 6), and having shown (through fieldwork) that the experimental design and data analysis methods prescribed by Taguchi—collectively called Taguchi methods (section 3.4.2)—has the potential to improve product quality to benefit the Lean apparel manufacturer (Chapter 7), this chapter completes the final link of the series of investigations by answering the fourth research question, based on the outcomes of the fieldwork at the case study organisation.

The fourth research question (RQ4) asks: *What drivers and what restraints do apply when Taguchi methods are actually being introduced in a mature Lean environment in the apparel industry?*

Section 8.2, the main section of this chapter is allotted to identifying the compelling forces (drivers) and restraining forces (inhibitors) that act towards the organisational change required to cement Taguchi style robust parameter design (RPD) experiments in the Lean manufacturing system being studied. In effect, section 8.2 answers the fourth research question. Section 8.3 is allotted to providing practical recommendations

towards an organisational change, based on the findings in the previous section. Section 8.3 is closely associated with the general research objective of the study (see section 1.6.3). Finally, section 8.4 provides a chapter summary.

8.2. THE FORCE FIELD ANALYSIS

In Lewin's Force Field Analysis (see section 5.7.1), the drivers are the forces that drive the organisation towards the requisite organisational change while the restraints (or inhibitors) are the forces that act as the restraints or blockers towards the requisite organisational change (Brassard & Ritter, 2010; Lewin, 1951; Luthans, 2011); the requisite organisational change being defaulting to Taguchi's RPD approach as the Lean apparel organisation's natural choice to solve variation problems due to uncontrollable factors.

As mentioned elsewhere (details in section 5.7.2), the researcher used the following sources to collect data/information to conduct the Force Field Analysis.

- Personal observations, namely the observations made by the researcher in the process of engaging herself with the organisational members involved in quality improvement (QI) activities (i.e. the QI team).
- Secondary data (records maintained by the case study organisation).
- Informal or unscheduled meetings with the mechanics and the quality manager.
- Scheduled short meetings with the decision makers: the quality manager, the planning manager, the production manager, the work-study manager and members of the "Lean team" (details given later).

Each driver and restraint that researcher identified are depicted in Table 8.1. The researcher's subjective evaluation⁶³ of the strength of each driver and restraint (in arbitrary units) at the time of making her observations, based on a 3 point scale (low/medium/strong), is depicted in Figure 8.1. Based on the researcher's subjective evaluation of each driver and restraint, the combined (resultant) effect of the drivers is only marginally higher than the combined (resultant) effect of the restraints, implying (a near) quasi-equilibrium, as assumed in Force Field Analysis (for theoretical underlings of Lewin's Force Field Analysis see section 5.7.1).

Table 8.1: The Compelling and Restraining Forces - The Current Position

Compelling Forces (Drivers)	Restraining Forces (Restraints)
D1: Ineffectiveness of existing problem solving tools	R1: Product design and development process being external to the factory
D2: Availability of standard approach to implement RPD	R2: Managers' statistical knowledge and their apprehension on statistics
D3: Repetitive production runs	R3: The nature of the product
D4: Non-value adding activities associated with machine setting up	
D5: Conduciveness to conduct large experiments	

⁶³ One can question whether a researcher's subjective evaluation on the phenomenon being observed is consistent with the duality principle (i.e. the observer being detached with the object/phenomena being examined) espoused in positivism; as mentioned in section 4.2.4, the researcher uses a positivistic paradigm (more precisely, a postpositivistic paradigm) throughout her research. The researcher's response to this question is that *there is no paradigm conflict* because nowhere in the research objectives that researcher mentions that researcher is measuring the compelling forces and the restraining forces (the researcher is only interested in identifying these forces). The aforesaid forces have been subjectively measured, just for the sake of completion of the Force Field Analysis.

the Lean organisation there is a so-called “Lean Team” (there were 5 members in the Lean team of the factory in which the case study was conducted) that teaches and sustains Lean principles.

One of the members of the Lean Team, who plays the role of the informal leader in the factory in sustaining Lean, explained that some problems often do re-occur even after they have supposedly provided a solution, using their existing Lean toolkit; the tools the informant mentioned included the Plan-DO-Check-Act (PDCA) cycle, the Black Box, the 5-Whys, the Pareto Chart, the Fishbone/Cause-and-effect diagram⁶⁴, and the A3 format; inspection of factory records verified that these tools have been heavily used in solving quality and operational problems (Appendix I).

The recurrence of problems was further explained by the quality manager who has 15 years of experience in apparel industry. In his own words:

We have been using many QI tools and techniques in this factory and elsewhere and there have been quite a few critical problems to which we have had no effective solution, in spite of our best efforts to provide a solution within the timeframe allotted to team-based problem solving.

Almost invariably, and justifiably, the manufacturing staff of the 31 factories belonging to Lean the organisation seem to have an “allocated time” for team based problem solving.

The Lean practitioners (the quality manager and the other problem solving team members that the researcher interviewed) strongly believed that if the right problem solving tool/technique has been correctly applied to identify the root-cause, the problem should not re-occur. To their disappointment, over the past nine years (the organisation

⁶⁴ The researcher observes that all 6Ms (men and women, money, machines, material, methods, and milieu) are well represented in the root-cause-analysis of the fishbone diagram (fishbone diagram is the primary tool the factory uses to identify the potential root cause/s). Representations are made from all relevant departments and units to identify the root causes and the contribution of each member in the team is appreciated irrespective of his/her rank. However, once a root cause is determined it no longer remains their (work improvement teams’) problem. Unfortunately, after the root cause is determined, it remains his problem or her problem. For example, if the root cause was found to be in the Machine root, it usually remains the chief mechanic’s problem. The implications of this are discussed in detail in section 8.3 (Practical recommendations to increase the uptake of Taguchi’s approaches).

launched Lean in its factories in 2005) there have been many verifiable instances where the exact same problem or a similar problem had re-occurred. As a Lean organisation they (the Lean Team as well as the quality manager, the planning manager, the production manager and the work study manager which whom the researcher engaged with) were very mindful of the waste associated with these recurring problems. They were confident that they have a good command over the tools/techniques that they apply and that the issue is not using a tool/technique incorrectly but using the wrong tool/technique!

This recurrence of the same problem clearly showed the lack of robustness of the solution provided by the tools/techniques used by the practitioners at times. As one member in the Lean team said:

“There is room for the robust parameter design approach that you are talking about” if it can be showed that it gives us the outcomes that we expect and if it fits to our culture”.

In the process of answering RQ3 the researcher demonstrated that Taguchi methods provide robust solutions.

In summary, the organisational members have experienced that the existing tools and techniques used to solve variation problems are ineffective. The problem solving mentality of the organisation means that the organisation welcomes a problem solving tool or a technique that fits to its culture (e.g. a tool/technique that embraces teamwork and respect for people). It was argued elsewhere (section 7.4.1) that Taguchi methods do fit to the culture of the Lean apparel organisation. Thus the “*experienced ineffectiveness of the existing tools/techniques*” and knowing that there is a better tool/techniques out there (Taguchi methods) is a driver for the organisational change.

The researcher’s estimation of the strength of the driver D1: “High”.

8.2.1.2. Availability of Standard Approach to Implement RPD (Driver D2)

In the process of conducting experiments and analysing the data using Taguchi methods (section 7.3.1), the practitioners (the QI team) realised that Taguchi methods use a standardised approach towards problem solving using: (a) brainstorming at the beginning, (b) a standardised design matrix (an orthogonal array), and (c) a standardised

performance criterion (the signal to noise ratio). This was seen as a positive sign by the practitioners: the quality manager, the production manager, the works study manager, the Lean Team, and the members of the QI team with whom the researcher worked with (see section 5.3.4).

Some examples of parallels the practitioners saw were:

- The main effects plots that were generated to identify the influential factors in Taguchi methods was seen as being equivalent to the use of bar graphs and the Pareto Chart to identify the “critical few factors” in Lean.
- The brainstorming that was used in Taguchi methods to identify potential control factors and noise factors was seen as being similar to the brainstorming being done in Lean for the root cause analysis (fishbone diagram, 5 Whys) in terms of the team composition (e.g. team leaders, quality controllers, quality checkers, technical personnel, the Lean Team representative), team involvement, and the general approach.
- In general, the visual tools used in Taguchi methods (e.g. the main effects plots) were seen as analogous to visual tools used in Lean.

In the process of conducting the experiments, the researcher and the QI team realised that brainstorming was the crucial component in Taguchi methods; the QI team saw a connection between brainstorming and its outcomes (the results of the application of Taguchi methods). One assistant production manager, who initially viewed the performance measure signal-to-noise ratio (SNR) in Taguchi methods as “*rocket science*” was quick to realise that SNR is just another standardised approach to pick right factor setting. Indeed it was a great advantage for the researcher to start her experiments in an environment that values standardisation.

Standardisation and visual control were found to be the most prominent features of the Lean case study organisation. The participants (the QI team) also saw a parallel between the use of visual cues used in Lean (for communication) and the visual tools used in Taguchi methods (e.g. the fishbone diagram, Pareto Charts and main effects plots); this was not the case when they had to confront with the statistical jargon used in

conventional DoE methods (the combined-array approach) when these were introduced by the researcher (see section 7.4.1).

The researcher's estimation of the strength of the driver D2: "Low".

8.2.1.3. Repetitive Production Runs (Driver D3)

Batch production is the production method used in apparel manufacturing, Lean or otherwise (Christopher, Lowson, & Peck, 2004; Taplin, 1996; Tewari, 2006). Some features of batch production in an apparel setting were found to be:

- Frequent changes based on fabric changes (colour) and style changes, and
- Low production lead time

Even though batch production seemingly acts as a restraint for the application of Taguchi methods, the fact is that the same style is produced over and over again (based on the pull signal from the customer) means that there is room for the application of Taguchi methods. In particular, the following were observed by the researcher.

If there is a colour change for the same style, some accessories (elastic, yarn, lace, labels etc.) are changed to match the colour. However, there is no change in the machine layout. Even though the same should apply to machine settings (because the style has not changed), in practice this does not happen. The machine settings are often changed in response to colour changes. It was found that this gives rise to quality issues such as measurement variations, stitch density inconsistencies, and presser foot marks on the garment.

It was also found that the machines have to be shut for a considerable length of time (5 to 30 minutes) to effect changes to the machine settings; however, the standard minute value of an operation varies from 5 to 40 seconds. This seems to put pressure on the staff to take quick remedial action for the problems. However, not all problems seem to have quick fixes (e.g. the variation problems the researcher studied). Furthermore, the researcher observed that a shift change usually results in several machine setting changes to suit the likings of the sewing operators even though nothing else but the operators have changed. The researcher inspected the records of machine downtimes at

the beginning of a shift; they were sometimes substantial. The work-study manager emphasised that the reason for substantial machine downtimes is often due to machine settings changes by an operator who begins a shift; the work-study manager also mentioned that the reason for machine downtime is so obvious that they do not even record the reason for the downtime. These observations mean that if there is the practitioner buy-in there is scope for Taguchi methods because robust settings can be recorded and reused when the same style is in production every time. This is what the researcher means by “repetitive runs”, the label for D3. This again is in line with ‘standardisation’ valued in Lean.

The researcher’s estimation of the strength of the driver D3: “Low”.

8.2.1.4. Non-value Adding Activities Associated with Machine Setting Up (Driver D4)

Mechanics play an important role in setting up the machines for a production run. As the chief mechanic (15 years of experience in the garment industry) explained:

Even though we arrange the machines for the necessary style and the team leader or job trainer checks and agrees with the machines settings for the relevant sewing operation (before a new production run begins), most of the time, we have to go and readjust the machines in the actual production runs. We always do not get on well with them May it is them who do not want to appreciate our contribution. The mechanics blame the sewing girls for tampering and they blame us for not setting machines properly in the first place.” We have a lot of experience in our trade and we know about machine settings than anyone else in the factory.

Unfortunately, the researcher observes that the climate in the organisation is such that the blame is passed on to the mechanic because the operators get more backing from the

top management, compared to the mechanic.⁶⁵ This was observed by the researcher as a dysfunctional feature of an otherwise a healthy organisation.

The contention of the mechanics (at the time of conducting researcher's fieldwork) is that sewing operators are doing adjustments to machine settings without an overall understanding about process variability (conceptually, this is equivalent to tampering). The researcher observes that all parties have come to experience that machine readjustments (i.e. adjustments after the mechanics have set the machine settings initially) generally result in worsening the process variability; as a remedial measure to reduce process variability the case study organisation has established new training programmes for the operators, team leaders, and the supervisors to educate them (mainly the operating staff and their team leaders) on the mechanical systems used in of sewing machines (including the systems used for various adjustments). Even though these programmes and workshops have been designed to improve productivity⁶⁶, according to the quality manager and the production manager, they have not resulted in the expected outcomes. The researcher observes that the limitations of the existing problem solving tools and techniques are a major reason for this. The records also show that there is clear evidence to prove that the aforesaid workshops (training programmes) have neither resulted in reducing machine downtimes nor reducing the instances the mechanics having to attend to machine setting adjustments (see Figure 8.2 constructed by the researcher from the factory records). All of the above evidence equate to non-value adding activities and waste.

⁶⁵ This could be due to mechanics' work being treated as a support process while the operators' work being treated as a value adding process. Understanding the complex behavioural relationships in the organisation was beyond the scope of the study.

⁶⁶ The researcher has had an opportunity of participating in these workshops and she found these workshops to be helpful in the following ways. The knowledge provided in these workshops does help a QI team to identify the potential factors to be considered in a RPD experiment. They also help in identifying and adjusting factor settings to conduct a RPD experiment. They also help the team to dig deep into the problem rather than searching the surface in the name of brainstorming.

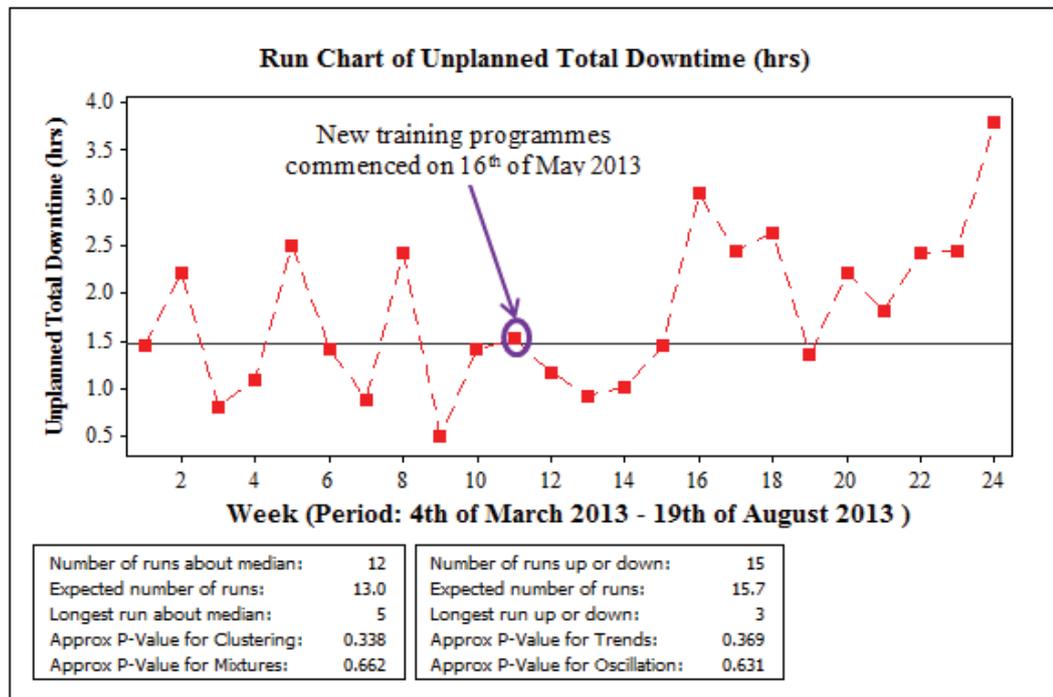


Figure 8.2: Weekly machine downtimes before and after introducing new training programmes

A solution for the frequent machine setting problem and non-value activities/waste mentioned above is to make the process robust against uncontrollable factors such as fabric type and the operator (the researcher demonstrated this in the previous chapter).

The researcher's estimation of the strength of the driver D4: "Medium".

8.2.1.5. Conduciveness to Conduct Large Experiments (Driver D5)

In the process of setting up experiments (Chapter 7), the researcher realised that setting up experiments involving a large number of trials is not a problem. In part, this was due to the keenness on the part of the practitioners to seek a solution to a critical problem, and in part due to low unit cost of production and the low time required to conduct the experiments. The literature (e.g. Montgomery & Runger, 2010; Shainin & Shainin, 1988) also support that Taguchi methods, which invite large experiments (but typically just one experiment for a given problem), are suitable in low unit cost high volume operations.

The researcher's estimation of the strength of the driver D5: "Medium".

8.2.2. The Restraints

Three restraining forces that could potentially inhibit in the requisite change were identified by the researcher during her fieldwork. These are described below.

8.2.2.1. Product Design and Development Being External to the Factory (Restraint R1)

The researcher observed that for most products (including the product studied in this thesis), a substantial part of product design and development takes place outside the factory. In some instances the overseas customer directly provides the design and the drawings to the organisation's headquarters based in Colombo. This seems to limit the application of Taguchi's robust parameter design (RPD) approach somewhat. This is because Taguchi emphasised that the RPD approach should actually be the second step of making a product robust against the variability of uncontrollable factors and that the first step should be, what he called the "system design", where the overall conceptual design is verified for variability (Gunter, 1987; Roy, 2010). Unfortunately the design verification takes place outside the factory and the researcher learnt that the case study organisation has very little involvement in the design verification; this may in part be due to the same design being produced for the customer (e.g. US and UK market) by many different producers worldwide. Taguchi emphasised that quality has to be "designed into product" offline prior to commercial manufacturing, rather than being achieved through online quality control (Taguchi, 1986; Taguchi & Clausing, 1990). This offline approach involves the system design (step 1) and the robust parameter design (step 2), and if step 2 fails to achieve the expected robustness, the tolerance design (step 3).⁶⁷ The researcher observed that product quality assurance needs in the factory usually arise once the product is being produced through the analysis of quality

⁶⁷ System design is about designing the operational system (e.g. operational factors), which requires technical knowledge on science and technology. Tolerance design stage is applied to tighten the tolerance of the operational factors (e.g. using better material, new equipment etc.) if the parameter design stage (explanation follows) is not sufficient to reduce the performance variation (Roy, 2010; Unal & Dean, 1991). Parameter design stage seeks to find an optimum performance of the product or process by experimentally determining the most appropriate level at which each experimental factor (control factor) should be set to minimise the performance variation caused by uncontrollable factors (noise factor) (Roy, 2010).

control records (i.e. on-line quality control). This necessitates a big step QI approach such as Lean Six Sigma.

For a Lean organisation, using the offline approach prescribed by Taguchi is highly beneficial because a substantial amount of waste can be reduced by tackling the variation problem at the product development stage. However, having to use parameter design without system design means that in an apparel manufacturing environment, the full benefit of Taguchi methods may not be attainable, unless the manufacturer collaborates with the customer (and vice versa) during product development; for example, the customer can obtain input from the case study organisation for design verification. Lean organisations are by definition collaborative organisations and moreover, the case study organisation is an important (major) supplier of the customer (meaning that the supplier has some bargaining power).

The researcher's estimation of the strength of the restraint R1: "High".

8.2.2.2. Managers' Statistical Knowledge and Their Apprehension on Statistics (Restraint R2)

The researcher observed that number of senior and middle managers and some operators hold graduate degrees belonging to applied sciences, management, arts and other disciplines. Even though they have been exposed to statistics, the researcher found that the staff has a real problem in using statistics to solve manufacturing problems (the staff is nonetheless very comfortable with descriptive statistics tools such as pie charts and bar graphs).

One senior executive in the planning department, who has 5 years of experience in textile industry informed the researcher that although he studied statistics in his undergraduate degree (double maths and physics) he never saw an opportunity to use what he learnt in his work.

The researcher found that a positive feature that sets apart the case study organisation from many other organisations in Sri Lanka is allowing employees to progress rapidly through the ranks by justifying his/her value to the organisation and this seems to limit the application of high level statistics (inferential statistics) in problem solving. The researcher found that a number of middle managers and senior executives who progress

to their current positions on merit have only a very basic knowledge on statistics. In interacting with staff the researcher found that conventional experimental design techniques (method II covered in Chapter 7) were beyond the limits of the participants (QI team). While Taguchi methods were viewed favourably by them it was not clear whether the participants would embrace these approaches without a sustained management initiative to disseminate them.

The researcher's estimation of the strength of the restraint R2: "Medium".

8.2.2.3. The Nature of the Product (Restraint R3)

Garments by definition are not rigid objects. The researcher found that it is hard to get an accurate measurement of a garment due to its stretchability (section 5.4.1). One has to be careful in taking the measurements of a piece of garment because the pressure of the finger is sufficient to make a substantial change in the measurement (2 to 3 mm based on field studies). Another issue related to the reliability of the measurement system is the use of very rudimentary measurement methods for taking measurements of the garments. This compounds the noise due to measurement system variation, which in turn reduces the effectiveness of the use of statistical performance measures (e.g. the SNR, statistical significance tests) to identify important factors through experimentation.

The researcher's estimation of the strength of the restraint R3: "High".

As evidenced from Figure 8.1, the combined effect of drivers is much greater than the combined effect of the restraints, which implies that, within a force field framework, once the current state is unfrozen (see section 5.7.1) it is possible for the organisation to move its organisational climate to the desired state of using Taguchi methods as a standard method to solve variation problems related to robustness.

In the next section the researcher provides practical recommendations to the desired state of using Taguchi methods as the standard choice to solve variation problems related to robustness.

8.3. PRACTICAL RECOMMENDATIONS FOR MOVING TOWARDS THE DESIRED GOAL OF USING TAGUCHI METHODS AS THE DEFAULT OPTION TO SOLVE VARIATION PROBLEMS RELATED TO ROBUSTNESS

Given that the desired organisational goal is to use Taguchi methods as a standard method to solve variation problems related to robustness in a Lean apparel manufacturing setting, and given that Force Field Analysis is a proven method of organisational change (Lewin, 1951; Luthans, 2011; Thomas, 1985), in order to meet the general research objectives of the study, the researcher proposes her recommendations for the requisite organisational change as follows. In this thesis, the researcher calls the requisite changes as “planned changes”, in keeping with the literature (e.g. Burnes, 2004; Schein, 1996).

Literature (e.g. Lewin, 1951; Luthans, 2011; Thomas, 1985) supports the notion that the most logical approach for moving towards the desired goal of any organisational change is to reduce the effect of the restraining forces rather than to increase the effect of the driving forces; this is because the former reduces the resistance to change.

One major requirement for moving towards the desired change (more technically “unfreezing” from the state of quasi-equilibrium, within a force field framework) is for the organisation to understand that there is a need for change and that the change is group (team) focused and not individual or organisation focused (Burnes, 2004; Cummings, Bridgman, & Brown, 2013; Lewin, 1951). Arguably, the greatest motivator for change is the “experienced ineffectiveness of the existing tools and techniques” (section 8.2.1.1) while the greatest incentive to use Taguchi’s robust parameter design approach (Taguchi methods) as an effective technique for quality improvement is that it is a team/group based approach and not an individual based approach (this was shown by the researcher elsewhere).

The following four recommendations are made to reduce the effect of the restraining forces.

8.3.1. Educating the Managers on Taguchi Methods

As shown in section 8.2.2.2, managers' lack of statistical literacy and their apprehension on using statistics to solve complex process problems (as mentioned in Chapters 5 and 7, making a product robust against uncontrollable variables is the complex problem being considered in the case study) is a sizable restraint for organisational change (restraint R2). The impact of this restraint can be reduced if it can be shown that Taguchi methods are statistically simple, yet very useful in solving product/process variability problems due to uncontrollable factors (variables). One must also keep in mind that a technical person has more of an applied focus rather than a theoretical focus, as far as statistics is concerned. Therefore the first recommendation for the planned change is to educate managers (who are actually the change agents) on Taguchi methods highlighting the applied focus of Taguchi methods. This initiative should come from the top management. However, the Lean team of the organisation should acquire the requisite statistics know how to implement this recommendation.

Antony and Antony (2001) showed to industrial engineers how Taguchi methods can be used to optimise the flight time of a paper helicopter. Their wider objective was to teach engineers how to teach Taguchi methods to the others to solve engineering problems. Antony and Antony used the graphical plots of Taguchi methods to good advantage to demonstrate its data analytic capability. This paper can be viewed as the Taguchi equivalent of Gorge Box's attempt to demonstrate how conventional design of experiments can be used by engineers to explain complex phenomena; Box leveraged on the statistical principles used in conventional DoE to show engineers how to use DoE to discover the optimum recipe of cake mix to maximise the (average) taste (Box & Jones, 1992b, 2001).⁶⁸

In some ways, what the researcher did in her fieldwork (Chapters 5 and 7) was similar to what Box (1992, 2001) as well as Antony and Antony (2001) did. Whereas Antony and Antony used a dummy object (a paper helicopter/plane) to demonstrate how

⁶⁸ One of the central arguments of Box is that statistics as a discipline strongly emphasise the need for mathematics rather than need for discovery and that this discourages engineers and physical scientists to use statistics. This is not to imply that engineers (and physical scientists) dislike mathematics; mathematics has always been a major component in engineering and physical science education.

statistically designed experiments can be used to solve engineering problems, the researcher used real objects (a critical product manufactured by the case study organisation) to demonstrate how statistically designed experiments (Taguchi methods) can be used to solve real problems. In doing so the researcher showed that the existing tools used by the case study organisation alone (e.g. one factor at a time experiments, fishbone diagram) are not sufficient to solve one of the most critical variation problems faced by the organisation at the time. The researcher's approach was an eye opener for the managers. They at least accepted that Taguchi methods are feasible as these methods are associated with less statistical jargon and are easier to use (e.g. in Taguchi methods the graphical tools can be used extensively to analyse the data).

The standardised nature of Taguchi methods was the other favourable feature found by the practitioners in the case study organisation. The researcher believes that the standardised nature of the methods, namely standardised orthogonal arrays, standardised optimisation goals (achieving the target response, maximisation or minimisation of the response) and corresponding SNRs can be further leveraged to educate the managers on Taguchi methods. It is hoped that this study serves as a starting point to educate Lean apparel practitioners on the use of Taguchi methods.

8.3.2. Leverage on the Strengths of the Taguchi Methods and Avoid Situations in Which the Methods are Likely to Become Ineffective

As mentioned in section 3.4.2 Taguchi methods have strengths as well as weaknesses. The strengths of Taguchi methods include the extensive use of team based technical knowledge at the design stage of the experiment, having a standardised performance measure (the SNR), standardised experimental designs (orthogonal arrays), and easy to interpret graphical tools. The weaknesses of Taguchi methods include having to have technical knowledge about how the process works, no room to build the knowledge sequentially through a series of smaller experiments to minimise risks, the SNR being not always an efficient performance measure, requiring a large number of trials and the exclusion of potentially important interactions between control factors. Strategically speaking, if Taguchi methods are viewed as operationally necessary, it is necessary to capitalise on the strengths of Taguchi methods while taking action to avoid situations in which the methods become potentially ineffective.

One way to avoid Taguchi methods becoming ineffective is to select QI projects for the application of Taguchi's RPD approach strategically. Likewise, one way to capitalise on the strengths of Taguchi methods is to have at least one person in the Lean team specialise in Taguchi methods in each factory to encourage the use of Taguchi methods in a more routine manner as the organisation achieves maturity on these methods. The technical knowhow on Taguchi methods and design of experiments in general, can be acquired through an appropriate Six Sigma course, although Six Sigma and Taguchi's RPD approach depart at conceptual level. More importantly, each factory should have a senior person (ideally the factory manager) who champions Taguchi methods into the working culture (organisational culture) of the factory. In many ways the role of this champion would be similar to the role of a Six Sigma Champion: strategic project selection and creation of QI specialists (Schroeder et al., 2008).

8.3.3. Show a Clear Connection Between Lean and Taguchi Methods

In Chapter 6 the researcher showed the empirical correlation between Lean and Taguchi's RPD approach at philosophical level. The actual methods associated with the RPD approach (i.e. Taguchi methods) were excluded in the empirical study because the respondents from whom the data were collected for the empirical study were not familiar with Taguchi methods. In Chapter 7 and particularly in this chapter the researcher showed a connection between Lean and Taguchi methods based on her fieldwork. The researcher views the similarities between the two methods as promising, in the sense it is unlikely to expect a major resistance for integrating Taguchi methods into the Lean culture by the organisational members (operators, their supervisors, and higher level managers). However, the nexus between Lean and Taguchi methods should be understood by the organisational members themselves and the application of Taguchi methods should result in tangible organisational benefits. The role of the change agent (e.g. the person who champions Taguchi methods in each factory) is to show this connection to minimise "resistance to change" (Thomas, 1985).

8.3.4. Collaborate with the Customer in Product Development

As mentioned earlier, product development normally takes place outside the factory and in spite of being an important supplier, the US customer does not obtain much input from

the case study organisation (the manufacturing supplier) in developing new products (e.g. new styles). This was viewed as a remediable restraint (section 8.2.2.1). A Lean apparel manufacturer of the calibre of the case study organisation can collaborate with the customer in product design and development much the same way as it collaborates with the customer for production scheduling (i.e. to effect pull production).

8.4. CHAPTER CONCLUSION

This chapter identified several drivers and restraints (section 8.2) within a force field framework. Five drivers and three restraints (Figure 8.1) were identified by the researcher. Each driver and restraint was explained in turn. The most influential drivers was *ineffectiveness of existing problem solving tools (D1)* while the least influential drivers were *availability of standard approach to implement RPD (D2)* and *repetitive production runs (D3)*. In particular, the organisation was trying to diagnose and solve every quality problem with the tools (e.g. the fishbone diagram, the Pareto Chart, and the 5 Whys) that were known to them. Similarly, the most influential restraints were *product design and development process being external to the factory (R1)* and *the nature of the product (R3)* while the least influential restraint was *managers' statistical knowledge and their apprehension on statistics (R2)*. The researcher argued that it is possible to break the status quo (“unfreeze”, in the language of Force Field Analysis) by lessening the effect of the restraints and capitalising on the high number of drivers being available. Researcher made four practical recommendations (sections 8.3) to bring about the desired organisational change of using Taguchi methods as a natural choice to solve variation problems related to robustness in the Lean apparel manufacturing setting being studied. There recommendations were to: (i) educate managers on Taguchi methods; (ii) leverage on the strengths of Taguchi methods and avoid situations in which the methods could likely become ineffective; (iii) show a clear connection between Lean and Taguchi methods; and (iv) collaborate with the customer in product development.

The next chapter, which is the final chapter of the thesis (Chapter 9), provides a summary of the study. This summary attempts to link the research questions, research objectives, methodology, and the key findings. The chapter also explains how the study

contributed to *new knowledge* (scope for further research is also given). A written reflection of the doctoral internship (final thoughts) is also covered in Chapter 9.

CHAPTER 9

CONCLUSIONS

9.1. INTRODUCTION

This chapter provides a summary of the study outlining specific conclusions. Section 9.2 describes how the key research driver of the study led the researcher to uncover the knowledge gaps, which in turn led to her research questions and research objectives. Section 9.3 provides the findings relating to each research objective. The methodology used to answer each research question, and results obtained are also briefly mentioned in section 9.3. Section 9.4 begins by showing the original contribution of the study to the field of quality and operations management. This is followed by a subsection on future research directions, in the light of the findings of the study as well as the study's limitations. Section 9.5 describes retrospective look at six sigma style quality improvement methods in relation to lean and Taguchi's RPD approach. Finally, section 9.6 provides the final thoughts of the researcher on her study based on what she experienced as a new and emerging independent researcher.

9.2. RUNNING THROUGH THE KEY RESEARCH DRIVER, KNOWLEDGE GAPS, RESEARCH QUESTIONS, AND RESEARCH OBJECTIVES

The primary driver of this study (section 1.4) is the conceptual overlap between the zero waste proposition espoused in Lean, and the zero defects proposition espoused in Taguchi's Quality Philosophy. This conceptual overlap prompted the researcher to dig deep into the extant literature on the concepts "Lean manufacturing" (Chapter 2) and Taguchi's Quality Philosophy (Chapter 3). Taguchi's Quality Philosophy holds that any deviation of the functional characteristic (quality characteristic) of a product from its target value causes an overall loss to society—the loss being proportional to the squared difference between the observed value and the target value.

The researcher found that Taguchi's Quality Philosophy is the building block of any robust parameter design (RPD) approach (details in section 3.4). Taguchi prescribed a

specific experimental planning method and an accompanying data analytic method—collectively known as Taguchi methods—which he believed would best suit the engineers in operationalising his quality philosophy. Taguchi not only added a new meaning to product quality but he also made statistically designed experiments accessible to engineers; up until Taguchi methods became known to the world outside Japan, statistically designed experiments were an esoteric topic used more by statisticians and researchers.

Whilst statisticians embraced Taguchi’s Quality Philosophy, they continued to use their own methods of designing experiments and analysing data; arguing that their methods, which are built on principles such as sequential learning⁶⁹ and modelling the response function, are statistically more efficient than Taguchi methods (details in section 3.4.3).

The researcher was surprised (although not completely) to find no substantial study that looked at how Taguchi’s RPD approach (or the alternative RPD approach advocated by the statisticians) could become an integral part of Lean. The researcher found that traditionally, Lean emphasised on adding customer value (and thereby the shareholder value of a firm) through operational efficiency. However, the researcher found that more recent literature (details in section 2.2.4) acknowledges building quality into the product at the product development stage (and thereby adding more customer value), which puts Taguchi’s RPD approach in a great position to become an integral part of Lean.

The reader should note that in framing the research questions, the researcher took into account the fact that while Taguchi’s Quality Philosophy could be accepted as a viable paradigm by practitioners in mature Lean organisations in apparel manufacturing, multifactor statistically designed experiments (let alone RPD) are a totally unknown quantity to them; there were only a handful of multi-factor experimental applications (see section 3.4.4) reported in the literature. The literature led the researcher into the following four research questions (for details on the knowledge gaps see section 3.6).

⁶⁹ Sequential learning puts less emphasis on teamwork/process knowledge (teamwork and process knowledge are a prerequisite in Taguchi methods) and more emphasis on discovery through statistics in a systematic fashion.

- RQ1 How does Taguchi's Quality Philosophy theoretically relate to Lean, in improving the operational performance?
- RQ2 What is the acceptance of Taguchi's Quality Philosophy by the practitioners of Lean philosophy in the apparel industry?
- RQ3 What are the statistical and operational merits and demerits (if any) of using Taguchi methods over conventional robust design experimental methods in solving important quality problems in apparel manufacturing?
- RQ4 What drivers and what restraints do apply when Taguchi methods are actually being introduced in a mature Lean environment in the apparel industry?

The third research question RQ3 as mentioned in Chapter 3 has both a practical (operational) element as well as a technical (statistical) element on Taguchi methods, relative to the response surface alternative. The practical (operational) element of RQ 3 was re-framed in Chapter 3 as follows:

RQ3a: Which robust parameter design experimental planning method suits the practitioners in mature Lean organisations in apparel manufacturing: the Taguchi method or the response surface alternative?

The technical element of RQ 3 was re-framed in Chapter 3 as follows:

RQ3b: Which data analytic method suits the practitioners in mature Lean organisations in apparel manufacturing: the statistical tools prescribed in Taguchi methods or the ones used in the response surface alternative?

As shown at the beginning of the study (Figure 1.2), the first two research questions RQ1 and RQ2 were directly tied into the first research objective of the study; the two sub questions of RQ3 (in effect RQ3) were directly tied into the second research objective; the fourth research question RQ4 was tied into the third research objective. In effect, answering the four research questions equated to achieving the three specific research objectives set out at the beginning of the study (section 1.6.2).

Figure 9.1 shows the logical flow of the research questions (hence the research objectives), where the methodology used to answer the research questions are found, and where the results and discussion on each research question are found. The *organisational context* for the study, namely “mature Lean organisations in apparel manufacturing”, needs a special mention as it has implications on the methodology.

The researcher observes that an organisation (be it apparel manufacturing or otherwise) could call itself a Lean organisation solely on the basis of the application of one or more Lean tools. For example, an organisation may use some form of work standardisation (e.g. in storage of goods, in operational procedures), keep the workplace tidy, and so forth, and call itself a 5S organisation, and therefore, they are a Lean organisation. Perfunctory application of Lean tools does not make an organisation Lean. Lean has a deeper meaning than this (details in section 2.2). A Lean organisation is an organisation that designs its process using customer value as the sole basis for improvement. A mature Lean organisation is a Lean organisation that has acquired the knowhow of process improvement (through organisational learning) through: (a) value stream mapping, (b) creating the flow of value added activities, (c) the pull system, and (d) continuous improvement to pursue perfection.

The researcher was interested in the integration of the RPD approach in mature Lean organisations only, because otherwise, organisations would not be able to comprehend whether or not Taguchi’s RPD approach does complement their Lean operations. The researcher selected a *single organisation* as the case study (multiple factories of this organisation were involved in theory testing to answer RQ1 and RQ2) mainly because she was not able to find multiple mature Lean manufacturing organisations in apparel manufacturing, within the resources available to her. No research is perfect; all research has limitations; the limitations of this study were set out in section 1.8.

9.3. CONCLUSION ON THE FINDINGS BASED ON EACH RESEARCH OBJECTIVE

The researcher used a post-positivistic research paradigm to achieve the research objectives (justification in section 4.2.4). It is important to note that research questions as well as research objectives were formulated by the researcher so as to enable her to use multiple data streams and multiple methods, in keeping with the best traditions of post-positivistic research (i.e. triangulation). The conclusions on the findings for each research objective are as follows.

9.3.1. Findings on Objective 1

Objective 1, which is shown below, was achieved successfully by finding answers to the RQ1 and RQ2.

Objective 1: To formulate and statistically test a theory that predicts and explains how Taguchi's Quality Philosophy and Lean management jointly contribute towards improving the operational performance in a mature Lean apparel manufacturing environment.

In addressing the first part of the research objective, that is, formulating a theory that predicts and explains how *Taguchi's Quality Philosophy* and *Lean* management jointly contribute towards improving the operational performance, the researcher developed a theoretical model that hypothesises relationships between Taguchi's Quality Philosophy and Lean Manufacturing, via the mediating variable Continuous Improvement (CI), to achieve the Manufacturing Process Outcomes. The theoretical model along with the strengths of the hypothesised relationships and their statistical significance are reproduced below for ease of reference (Figure 9.2). The theoretical model was developed based on the extant literature. The model consists of a number of good features: parsimony, inclusion of a mediating variable (which is CI), relevance to practice, clear definition of the boundary conditions of the theory (details in section 4.3.2), and clear operational definitions for each construct in the model.

In moving to the second part of the research objective (model testing), the theoretical model (Figure 9.2) was tested using 318 cases of usable data collected via a *survey questionnaire* from 31 factories (dispersed across several administrative districts in Sri Lanka) belonging to the case study organisation, which has matured as a Lean organisation in apparel manufacturing. The respondents of the survey were front line workers, their supervisors, and higher level managers. The researcher argued that although the factories belonged to a single organisation (details in section 4.5) there is sufficient diversity within factories and between factories to make the findings sufficiently generalisable.

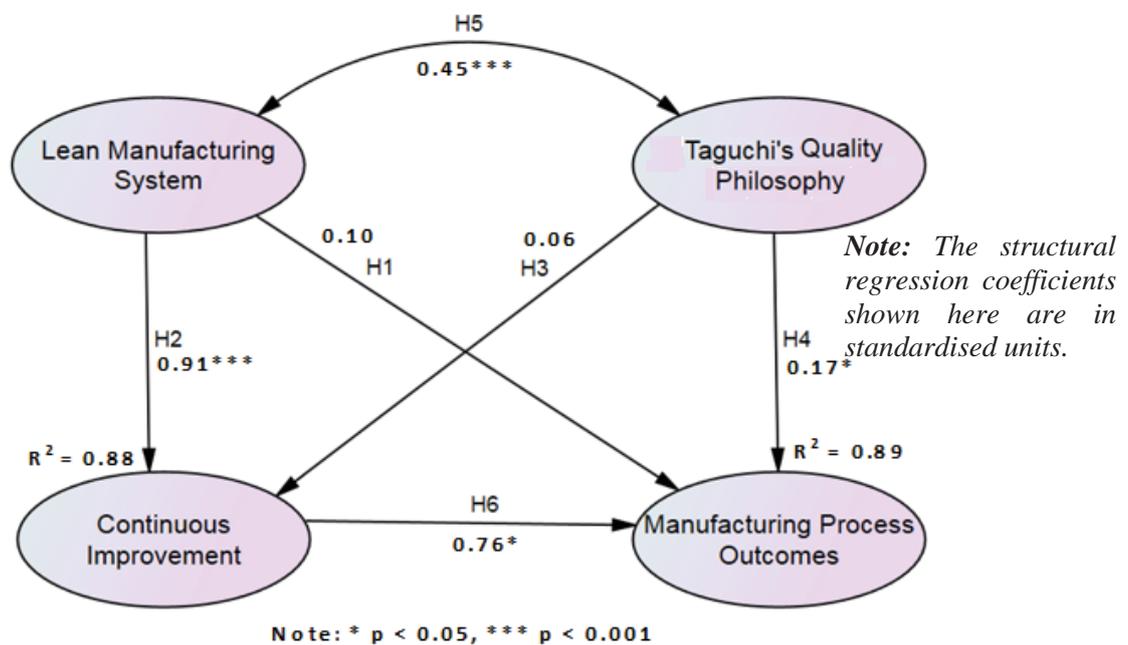


Figure 9.2: The structural relationships between constructs and parameter estimates

The theoretical model was found to be a good covariance fit to data, in terms of the major global-goodness-of-fit indices ($\chi^2/df = 1.71$, RMSEA = 0.047, CFI = 0.963, NFI = 0.918, and PCLOSE = 0.621) used in covariance based Structural Equation Modelling (CBSEM). In the language of CBSEM, the results imply that the researcher's theoretical model is tenable. As it would become evident to the reader from Figure 9.2, data supported four of the six hypothesised relationships in the model. The two relationships that were not supported by data were the direct effect of the Lean Manufacturing System on Manufacturing Process Outcomes (H1) and the indirect effect of Taguchi's Quality Philosophy on Manufacturing Process Outcomes through the

mediating variable Continuous Improvement (H3). Table 9.1 outlines the possible reasons for non-support of H1 and H3.

Table 9.1: Possible Practical Reasons for Non-Support of H1 and H3

Hypothesis	Suggested Reason
H1	<ul style="list-style-type: none"> • CI is such an integral part of Lean that CI fully mediates the relationship between the cause (the Lean manufacturing System) and the effect (Manufacturing Process Outcomes) leaving no room for the former to have a direct effect on the latter. The respondents may have perceived that Manufacturing Process Outcomes are achieved solely through CI and that the manufacturing system itself plays no direct role in achieving its operational outcomes.
H3	<ul style="list-style-type: none"> • The respondents would not have had any experience whatsoever in using statistically designed experiments to bring Taguchi's Quality Philosophy into fruition through CI projects (e.g. a Six Sigma style project). • The respondents may have perceived that Taguchi's Quality Philosophy has some merit in developing products to achieve manufacturing process outcomes (a significant H4 supports this) but not in a CI context.

The reader may refer to section 6.6 for a full discussion on the results pertaining to all the hypotheses. In summing up, the researcher concludes that her theoretical model was found to be acceptable both technically (a good covariance fit to data) and practically (the supported hypotheses make practical sense).

9.3.2. Findings on Objective 2

Objective 2, which is shown below, was achieved successfully by finding answers to RQ3.

Objective 2: To assess the suitability of Taguchi methods on statistical grounds as well as practical grounds to handle a substantial waste reduction problem faced by a mature Lean apparel manufacturer and compare these techniques with traditional DoE techniques in the setting studied.

Needless to say, to assess Taguchi methods on statistical grounds as well as practical grounds (to handle a substantial variation reduction problem), it becomes necessary to design and execute a RPD experiment that has the potential to reduce variation in a Lean organisation, and engage with the practitioners as much as possible—much the same way as “the proof of the pudding is in the eating”. Thus the researcher designed, developed and executed RPD experiments⁷⁰ in one of the factories belonging to the Lean case study organisation. Essentially, the researcher and the QI team concentrated on the *sewing process* as the variation problem appeared to be originating from sewing, rather than cutting or finishing—the other two major processes in apparel manufacturing. The experimental unit used in the experiments were a particular style of women’s intimate apparel (for details of the product, the customer, and the quality problem, see section 5.3.3) produced to a valuable customer who is renowned globally as a fashion provider for the high-end market.

The fieldwork was intense (details in Chapter 5), requiring the researcher to spend about 580 hours for data collection (both quantitative and qualitative) alone. The experiment was designed in such a way that it could be analysed via both Taguchi methods (method I) as well as the alternative method: response surface approach to RPD (method II). The two methods were compared on the data analytic front as well as the operational front, because any RPD experiment (be it based on Taguchi methods or based on the response surface method to RPD) has a technical element as well as an

⁷⁰ One main experiment and a pilot forerunner experiment, along with baseline studies to assess the process prior to the RPD experiment.

operational element (see section 9.2 for the explanation provided by the researcher for splitting RQ3 into two components).

Perhaps unsurprisingly, data analysis based on both Taguchi methods and the alternative method (this method served as the reference against which Taguchi methods are assessed) provided similar directions to the QI team as to how they should go about in adjusting the sewing parameters to make their process as robust as possible. Although the response surface approach to RPD provided more information to the experimenters through data analysis compared to Taguchi methods, the researcher found that the latter is more suitable than the former for the specific organisational context. Table 9.2 depicts the merits and demerits of Taguchi methods, as identified by the researcher (Table 7.5 reproduced for ease of reference).

Table 9.2: Merits and Demerits of the Taguchi Methods in the Context Studied

<i>Technical Merits</i>	<i>Technical Demerits</i>
Highly standardised	Require larger number of experimental runs
Easy to adopt and can apply with limited statistical knowledge	Does not build an empirical model (a regression equation) as such to predict or explain the process being studied
<i>Operational Merits</i>	<i>Operational Demerits</i>
Suitable for low unit cost high volume industries	Rely on prior engineering and technical knowledge to decide what factors are potentially important and at what levels they should be manipulated in setting up the experiment; prior knowledge may not be always be available in new product development
In line with the Lean culture	Only able to ‘pick the winner’; does not provide adequate information as to what happens to the process if the settings are moved within and outside the manipulated factor settings

9.3.3. Findings on Objective 3

Objective 3, which is shown below, was achieved successfully. As stated earlier, this objective was achieved by finding answers to the RQ4. Findings on the RQ3 were also indirectly used in achieving this research objective.

Objective 3: To identify and describe the drivers and restraints associated with a potential change management intervention to integrate Taguchi's RPD approach in a mature Lean organisation in apparel manufacturing.

Implementing Taguchi methods (more technically precisely, Taguchi's RPD approach) in an environment that is not familiar with those methods supposedly involves a certain amount of *resistance to change*. The role of the change agent is to understand what drives and what inhibits (restraints) the change, so as to make the transition as smooth as possible by taking appropriate action. The researcher was not a change agent nor had she had any vested interest on the case study organisation. As no attempt was made by the case study organisation to make any organisational change to implement Taguchi methods, at best, all what the researcher could do was to identify and describe the drivers and restraints governing a potential organisational change management intervention at theoretical level. The researcher used "Lewin's Force Field Analysis" (details in section 8.2) as a theoretical tool to map the drivers and restraints that affect a potential change management intervention; the research question relevant to Force Field Analysis is the final research question (RQ4).

The drivers and restraints as well as their relative strengths were identified by the researcher through qualitative data collection. The researcher acknowledges that while the drivers and restraints that the researcher identified may apply to other Lean organisations in apparel manufacturing, the relative strengths of these drivers and restraints may vary from one apparel organisation to another. The limitations of a single case study have been acknowledged at the very outset (section 1.8).

The qualitative data to address objective 3 were actually collected whilst the researcher was interacting with the staff of the case study organisation in conducting the RPD experiments as well as other studies that preceded the experiments. Personal observations, interviews, secondary data (company records and forms, minutes of the meeting, and visual charts such as performance charts) were the different data collection methods the researcher used to gather qualitative data for the study to answer RQ3 and RQ4.

The most influential driver was found to be the *ineffectiveness of existing problem solving tools (D1)*; moderately influential drivers were found to be the *non-value adding activities associated with machine setting up (D4)* and *conduciveness to conduct large experiments (D5)*; the least influential drivers were found to be the *availability of standard approach to implement RPD (D2)* and *repetitive production runs (D3)*. Likewise, the most influential restraints were found to be *product design and development being external to the factory (R1)* and *the nature of the product (R3)*; moderately influential restraint was found to be *managers' statistical knowledge and their apprehension on statistics (R2)*.

9.3.4. Findings on the General Research Objective

General Objective: *To formulate a practically useful set of recommendations that enable manufacturing organisations to increase the uptake of robust design methodologies for improving their operational performance.*

Finally, the general research objective was achieved by providing a number of recommendations to implement the requisite organisational changes, should the Lean organisation decides to integrate Taguchi methods within their operations. These recommendations were made based on the experience the researcher gained in answering RQ3 and RQ4 (details in section 8.3). The recommendations made by the researcher were as follows:

- i. Educate managers on Taguchi methods.
- ii. Leverage on the strengths of Taguchi methods and avoid situations in which the methods could likely become ineffective.
- iii. The change agent should show a clear connection between Lean and Taguchi methods until Taguchi methods becomes part and parcel of Lean tools.
- iv. Collaborate with the customer in product development.

The researcher acknowledges that these recommendations might be too organisation-specific to become generalisable.

Having answered the research questions and having achieved the research objectives, the researcher concludes that her overall research hypothesis shown below stays in contention.

“Taguchi’s robust parameter design approach can complement Lean”.

9.4. THE ORIGINAL CONTRIBUTION AND FUTURE RESEARCH

9.4.1. The Original Contribution of the Study

This subsection describes the original contributions the study makes to theory development and theory testing, in the field of quality and operations management.

Novelty

The most notable original contribution the study makes to the field of quality and operations management is that this study attempted to examine the nexus between Lean and Taguchi’s RPD approach in a holistic way to explain how the latter complements the former, in explaining manufacturing outcomes. Other than studies that reported a specific application of Taguchi methods in a Lean context, no study has examined how two seemingly complementary concepts—Lean and Taguchi’s RPD approach—could be combined at theoretical and practical level. One possible reason for this could be (judging by the researcher’s literature review) that past researchers may have considered these two concepts as self-contained concepts—Lean as an approach that adds customer value by eliminating waste (and non-value adding activities) through CI, and Taguchi’s RPD as an approach that adds customer value at the product development stage. The researcher observed from the latest literature that this silo approach need no longer be true (details in sections 2.2.2 and 2.2.4) and that there is scope for the integration of Taguchi’s RPD in Lean, based on contemporary Lean thinking.

Comprehensiveness

Another original contribution the study makes to the field of quality and operations management comes from the study's comprehensiveness. The study identified from the literature that Taguchi's RPD approach consists of three interlocking elements: Taguchi's Quality Philosophy, Taguchi's teachings on how a RPD experiment should be planned and designed, and Taguchi's data analysis methodology (section 3.4.2). Through dedicated research questions, the study examined to what extent each element of Taguchi's RPD approach becomes compatible with Lean.

RQ1 and RQ2 were formulated to examine the compatibility of Taguchi's Quality Philosophy (the first and the primary element of Taguchi's RPD approach) with Lean. RQ3 was formulated to examine to what extent the experimental planning methods as well as data analytic methods prescribed by Taguchi (as mentioned earlier, collectively known as Taguchi methods in the literature) become compatible with Lean. RQ4 was formulated to understand the potential practical implications of implementing Taguchi methods in Lean. Therefore, the researcher contends that her study is comprehensive in terms of its scope. This comprehensiveness also provides multiple evidences on the compatibility of the two primary concepts under consideration: Lean and Taguchi's RPD approach.

9.4.2. Future Research Directions

It is normal for a research study to contain multiple limitations. In spite of the limitations, the study does serve as a foundation for future research on the relationship between Lean and Taguchi's RPD approach in explaining manufacturing process outcomes.

A number of future research directions can be identified based on the limitations of the study as well as the findings of the study. Firstly, the theoretical model (Figure 9.2) developed by the researcher to predict and explain how Taguchi's Quality Philosophy complements a Lean Manufacturing System, is a parsimonious one. There is scope for augmenting the model. Secondly, the external validity (generalisability) of the findings based on the theoretical model is somewhat restricted, due to the sampling frame chosen by the researcher (apparel manufacturing only, and only for factories belonging to the

same organisation). Thirdly, the theoretical model was tested based on cross-sectional data. As will be discussed in section 9.4.2.3, longitudinal data can add more practical validity to the findings. In addition, the study did not involve non-Lean manufacturing organisations as a control group to determine to what extent a Lean culture favours a non-Lean culture in the uptake of Taguchi's principles, practices, tools and techniques (see section 7.4.4 for the researcher's conclusions on the uptake of Taguchi's principles, practices, tools and techniques in a Lean culture). The researcher's findings (section 7.4.4) need to be further verified through a comparative study involving Lean and Non-Lean manufacturing firms. Finally, the fieldwork used to test the third and fourth research questions were based on data collected from a single case study. Multiple case study data would add more insights to the phenomenon being observed; a multiple case study would also reinforce the generalisability of the findings related to the technical merits and demerits of Taguchi methods in Lean (RQ3); more importantly, a multiple case study would certainly enhance the findings on organisational change management dynamics (RQ4). These points are discussed in turn.

9.4.2.1. Augmenting the Model

The researcher's model does not take into account any moderating effect that may exist on the hypothesised causal relationships. It could be quite possible that certain contingency factors could moderate the hypothesised relationships. Therefore, future research may be directed towards identifying potential moderating factors and their effects on the hypothesised relationships. Some moderating factors researchers could consider might be the organisational culture type, the plant size, and the degree of Lean maturity. The more moderators one uses, the more complex the model becomes, and a complex model may not necessarily be more informative than a parsimonious model. As such, moderating factors should be chosen carefully.

9.4.2.2. Widening the Sampling Frame for External Validity

The sampling frame can be widened and diversified in future studies in many ways. One way to do this is to go for as many different Lean organisations as possible (within and outside regional and national jurisdictions). The proposed theory is envisaged to be generalisable across a wide variety of firms (apparel was not considered as a requisite

organisational context in the theory development phase). As such, the sampling frame could include Lean manufacturing firms belonging to a wide variety of industries.

9.4.2.3. A Longitudinal Study for Enhancing Practical Validity

The theoretical model was tested using cross-sectional data, which prompted the researcher to use a correlational research technique, namely, Structural Equational Modelling. Causality can be established more definitely with longitudinal (time series) data. In particular, future research may be directed towards understanding to what extent Lean manufacturing organisations actually make gains on process outcomes after they gain experience in using Taguchi's RPD approach.

9.4.2.4. A Multiple Case Study

A single case study has its positives as well as negatives. A positive is being able to conduct an in-depth analysis and greater opportunity to understand the context being studied. The negative is low generalisability. The researcher is not referring generalisability in a statistical sense—that is, inferring from the sample to the population under parametric assumptions; such generalisability is inconceivable with qualitative data. The researcher is referring to analytical generalisability. The more firms being studied, the findings become the generalisable, in an analytical sense.

In this study, research questions 3 and 4 were answered based on a single case study. Research question 3 (RQ3) concerns the use of RPD approaches in a *mature Lean manufacturing* context in relation to the *apparel industry*. The researcher selected the best possible case that represents this context (maturity in Lean, in apparel manufacturing). While specific organisational culture was a factor in answering both RQ3 and RQ4, it was not as significant a factor in answering RQ3 as in answering RQ4. Besides, most findings on RQ3 (see Table 9.2) are consistent with the literature. Therefore, the researcher argues that inclusion of multiple organisations would not have necessarily increased the analytical generalisability of the researcher's conclusions, in relation to RQ3.

Unlike RQ3, RQ4 looks at organisational change management dynamics. Therefore, organisational culture plays a larger role in answering RQ4 than in answering RQ3.

Inclusion of multiple organisations would enable a researcher to understand how each driver and restraint for the requisite organisational change management intervention vary from one organisation to another, providing richer information to the reader. Therefore future studies could be directed towards including multiple organisations in understanding organisational change management dynamics in relation to implementing Taguchi's RPD in their respective Lean environments. The researcher also advises that case selection should involve Lean organisations that are active in product development.

9.5. A RETPROSPECTIVE LOOK AT SIX SIGMA STYLE QUALITY IMPROVEMENT METHODS IN RELATION TO LEAN AND TAGUCHI'S RPD APPORACH

Taguchi's RPD approach refers to parameter designs, based on Taguchi's prescriptive criteria of designing experiments and analysing data to actualise his quality philosophy. It is important to realise that Taguchi's RPD approach is what Taguchi saw as the way to go in the 1960s, as far as Japan is concerned—the objective being to produce high quality products in an efficient and effective manner, to capture the Western markets. The technology has evolved immensely since the Taguchi era, especially in the past 2-3 decades. For example, powerful computational methods to solve complex engineering problems are no longer a luxury to the everyday engineer. Similarly, the customer and market environment has evolved rapidly, keeping step with the technological change. Products need to be designed, developed, and introduced to the market very quickly, which means that building physical prototypes and/or conducting large experiments may not be an option to some industries. Therefore, one can argue that what was ideal to Japan and the rest of the world fifty years ago need not necessarily be ideal today. In any case, a retrospective look at Taguchi's RPD approach requires a revisit on Taguchi's quality philosophy (section 3.4.2.1).

The two primary aspects of Taguchi's quality philosophy are loss to society from the time a product is shipped to the customer, and the customer's loss due to performance variation of the product (i.e. the product's lack of robustness). Another very important aspect of Taguchi's quality philosophy is continuous improvement and cost reduction, in order to stay in business (see section 3.4.2.1 for Kackar's delineation of Taguchi's quality philosophy). Lean gurus Womack and Jones termed the two primary aspects

embedded in Taguchi's quality philosophy as *Lean consumption*, without any explicit attribution to Genichi Taguchi. In hindsight, this should not surprise scholars, because Womack and Jones operationalised Lean based on their experience with the Japanese industry (mostly Toyota), which follows the principles of Deming and Taguchi to the letter! Therefore, with the exception of Deming's precepts on continuous improvement (e.g. single source suppliers, collaboration, pursuing perfection and other points that Deming articulated), arguably, there is no other precept that parallels the Lean philosophy as Taguchi's quality philosophy.

However, it is important to note that Six Sigma evolved more recently to fulfil a very important need in the industry—making quality improvement programmes exciting to the top management of a business. Six sigma is a quality system consisting of leadership, people, practices, tools, and techniques that can make quality improvement programmes very profitable. In a Six Sigma organisation, the return on investment is the only criterion top managers use to sanction a quality improvement project. Reducing variation to unprecedented levels, which translates to elimination of defects and defectives, remains the core aim Six Sigma. Having conducted fieldwork, and having reviewed the literature, the researcher sees several differences between Taguchi's Robust Parameter Design approach and Six Sigma.

Online-Offline Distinction

Firstly, Six Sigma has been designed to improve quality using online quality control, in the sense, the beginning of a quality problem (the Define stage of the DMAIC process) and ending of a quality problem (the Control stage of the DMAIC process) are underpinned by online quality control (e.g. the use of control charts and process capability analyses). Taguchi's RPD approach on the other hand emphasises on offline quality control. Stated alternatively, Taguchi's RPD approach emphasises on building quality at the design stage to ensure greater customer satisfaction and minimum loss to society. The researcher acknowledges that Design for Six Sigma (DFSS) corrects the aforesaid shortcoming of Six Sigma, within a Six Sigma framework. Therefore, the researcher goes on to compare Taguchi's RPD approach with DFSS from this point onwards.

Consultant Driven Versus Philosophy Driven

DFSS has one advantage over Taguchi methods. However, this advantage can very easily become a significant disadvantage. DFSS, at least in theory, is not aligned to any particular tool or technique. For example, DFSS does not emphasise that a quality improvement team should necessarily use Taguchi methods to achieve robustness in a product design, although DFSS was popularised by Taguchi's close colleagues (e.g. Subir Chowdhury) as a way of implementing Taguchi's tools and techniques, with a Six Sigma quality system. The advantage of DFSS over Taguchi methods is that because DFSS is not aligned to any particular tool or technique (DFSS is open to any good tool/technique), the Six Sigma specialist—the black belt or a green belt depending on the nature/impact of the quality improvement project—who plays the role of the consultant, can pick any tool or technique at his/her disposal that he/she thinks best fits the situation. For example, the consultant can use mathematical programming to accomplish a robust optimisation (i.e. to design a product that is insensitive to perturbations in design parameters) or use matrix methods within an axiomatic framework (see section 3.4), or even use an altogether different technique to achieve design quality, such as achieving greater reliability. With this flexibility comes what is known as “tool pushing” by the consultant, something that has shown to be problematic in the industry to disseminate design methodologies (see section 3.4.4.4).

In the fieldwork, the researcher found that Lean practitioners in the apparel industry seek ownership in quality improvement. If DFSS is introduced in a Lean organisation as a consultant-centred, “tool pushing” quality improvement practice, it is very unlikely that DFSS will be accepted by Lean practitioners. The researcher took great care (see Chapters 5 and 7) to ensure that she does not become a tool pusher! If DFSS is introduced in a Lean organisation as a method of realising Taguchi's quality philosophy using a standardised approach—in other words, Taguchi methods in all but name—there will be good chance of DFSS being accepted by the practitioners. In fact, this is exactly what the researcher found reroute answering her fourth research question (see Chapter 8 for the results).

Type of Industry

An important question is what level of mathematical/statistical sophistication a particular industry needs to solve their standard problems, such as designing high quality products. In consumer products, high quality at low cost (an important element in Taguchi's quality philosophy) is a basic requirement. Such an industry may not require high level of mathematical/statistical sophistication in product design. This basically eliminates all the alternative robust design methodologies. In an apparel industry that practices Lean, Taguchi's RPD approach appears to have a clear advantage over other robust design methodologies.

9.6. FINAL THOUGHTS

In this final section of the final chapter, the researcher looks at her study in retrospect to highlight certain experiences that she gained in conducting her doctoral study. The objective of this is to inform future new researchers the problems that they may come across in designing and conducting similar studies. This section may also benefit researchers who may want to pursue their research along the lines of the future research directions provided by the researcher (section 9.4.2).

9.6.1. Data Collection in Some Settings Involves Not Only Immense Work, but Also Tact and Diplomacy

An important feature in the researcher's methodology is "triangulation". The triangulation approach is adopted in social research to study the same phenomenon using different methods and different data to get a richer perspective of what is being studied and what is being uncovered—the objective being to increase the validity of the study. The researcher used the post-positivism triangulation approach. More specifically, she used the *between method triangulation* approach where different methods are used on the same object.

In recapping the work the researcher did, the initial understanding of the concepts, the knowledge gaps (and therefore the research questions) were obtained through the literature (Chapters 2 and 3). The first research objective was achieved by testing the researcher's theory (more technically, the theoretical model) that was developed

through the available literature, and testing it through the quantitative data collected from respondents ($N = 318$) in the 31 factories belonging to the case study organisation; the data were collected through a questionnaire developed (through the literature) by the researcher. The second and the third research objectives were achieved by conducting fieldwork in a specific factory, which enabled the researcher to collect the required quantitative and qualitative data to achieve the above research objectives. Indeed, this factory was the researcher's laboratory in every respect but the name! The researcher conducted a major experiment (preliminary experiments and other fieldwork such as assessing the stability and capability of the existing process, and calibration of the measurement system preceded) to solve a real problem occurred in the existing process; the experiment was conducted in a Lean manufacturing setting involving substantial teamwork; the experiments, process stability assessment, process capability assessment, and calibration of the measurement system involved quantitative data collection. Qualitative data were collected through personal observations, formal and informal interviews; in addition, secondary data (e.g. reports, charts, quality records, minutes of meetings etc.) were also collected. All these activities required substantial fieldwork.

In conducting fieldwork, the researcher required full corporation of the staff: from the frontline workers (mainly the ones who sew the garments, who were nearly always females in the 18-30 years age range) through to the manager of the highest echelon in the factory. The researcher had to change gear back and forth when she communicated with the frontline workers and the managers (particularly the middle and top managers). If there is a phrase to describe the researcher's action, that would be "*acting in an ethically responsible manner*". To managers, the researcher was a doctoral researcher from New Zealand⁷¹ who is out there to conduct a research and share her knowledge with them, which, in the long run, could benefit them (their apprehension to statistics notwithstanding!) and their organisation.⁷² To frontline workers (most of them came from rural areas to work in the city and they had no exposure to what was happening in the scientific enterprise), at least at the beginning, the researcher was an experimenter⁷³

⁷¹ The four words Sri Lankans associate New Zealand with (in the hierarchical order) are: Anchor milk, lush greenery, cricket, and rugby ("the haka" to be more specific).

⁷² Some of the key managers were known to the researcher beforehand because she conducted her undergraduate project as a third year engineering undergraduate (6 years ago) in this factory; this and the researcher's credentials also helped.

⁷³ In Sinhalese, the word experimentation translates to "trailing"; the popular Sinhalese media portray experiments as risky ventures that seldom result in public gain. This does not help!

who is out there to do something that may work negatively against them, or at best, has no benefit to them; the researcher had to work out a strategy to break the communication barrier.

In the Lean environment in which the researcher worked, she realised that the only way to win the trust of the blue collar workers (also see section 5.3.1) was to be one of them (literally), by working with them. The girls would never call the researcher by her first name only (in the Sri Lankan culture, it is not being considered proper for a blue collar worker to call an engineer by their first name only) but hours of engagement with them and empathising with them meant that they gradually started replacing the salutes “engineer madam” and “Pramila madam” with the salute-neutral word “you” or the mildly-saluted word “Pramila Miss.”⁷⁴ This was the time the researcher realised that they are ready to co-operate and the researcher has to move on. Apart from showing empathy to blue collar workers and remembering to call them by their name (rather than calling “you”), the researcher chose words carefully, depending on whom she spoke to. Another requirement that was needed in the fieldwork was a great deal of poise and composure, on the part of the researcher. The most intrinsically rewarding part of the fieldwork was the dual role played by the researcher (a collaborator before a blue collar worker and an engineer/researcher before a manager), arguably, without a role conflict.

9.6.2. Knowing the Jargon and the Lingo Beforehand Helps in the Fieldwork

It goes without saying that “a forewarned is forearmed”. The researcher had prior professional working relationships with the apparel industry; the researcher has also worked before in the factory as an engineering undergraduate to conduct one of her undergraduate project. All this meant that the researcher was familiar with the jargon used in Lean and the apparel industry. This advantage meant that the researcher was able to complete her fieldwork in the factory in 22 weeks, which would otherwise have taken possibly, 44 weeks to complete!

⁷⁴ In workplace conversations, Miss XYZ and “XYZ Miss” have somewhat different meanings in the Sinhalese language. The former (e.g. Miss Pramila) is used by English speaking managers when they talk to a female executive. “XYZ Miss” (e.g. Pramila Miss) is used by blue collar workers when they talk to a lower to middle-level female executive in Sinhalese (nearly always, blue collar Sri Lankan workers do not speak English).

The researcher would also like to mention that in addition to engaging with the staff at the factory, the researcher was also following up the progress of the responses for her questionnaire, from the human resource managers in the factories of the Lean organisation (details in section 4.5). As mentioned earlier, data collected through the questionnaire was used to test the researcher's theoretical model, and thereby achieve the first and primary objective of the study. If the researcher played a rather passive role in dispatching the questionnaires to the 31 factories and waited for things to happen, she would not have received as many responses as she did for her study. The researcher's familiarity with the Sri Lankan culture and fluency in the local vernacular helped her in contacting the human resource managers and engaging with them in conversations (not to mention visiting some factories) in order to get their fullest cooperation for the survey.

9.6.3. Design of Experiments is Seriously Challenging When Human Interactions are Involved

The researcher was fortunate to be enrolled in coursework (a 15 credit paper) on Design of Experiments at Massey University, the week after she began her studies (tutoring on DoE in the labs in the subsequent year reinforced the researcher's technical knowledge on DoE). This meant that she had a good understanding on the technical aspects of DoE when she began her fieldwork. During and after conducting the variation reduction experiments only the researcher realised that real DoE is not in the computer lab but in the field! Conducting DoE in the work environment was very challenging because some of the assumptions that the researcher made in conducting the experiments came under serious threat; this was mostly due human acts, which might have taken place with the best of intentions. The following three examples best illustrate these problems.

9.6.3.1. The Regular Cut Versus the Training Cut

The researcher wanted 3x100 components (the front panel, the back panel and the gusset) of a particular design of women's briefs being cut by the cutting department for her main experiment. Their cutting docket would indicate whether the job is for a regular run or for a training run to train the sewing staff. The cutting department is programmed to work in this binary mode and cutting for an experiment would equate to

cutting for a training run, as far as the cutting department is concerned. The researcher observed that in spite of being a senior cutter, and in spite of the researcher observing the pieces being cut, the cutter did not take (seemingly) the same meticulous care that he takes when he cuts the panels for the regular run (the panels cut for the regular run are sewn for customers such as Victoria's Secret, USA). This put the researcher's assumption that "back coverage variation comes from sewing and not from cutting" (see section 7.5 for example) under threat.

9.6.3.2. An experienced Worker Versus an Inexperienced Worker

Operator skill level (handling technique) was one of the noise factors in the main experiment (see Table 5.8 for example) and the researcher wanted two sewers released for her experiment: a highly experienced worker (+1 level of the noise factor) and a low experience worker (-1 level of the noise factor). Both workers worked diligently in the experiment and the conversations the researcher had with them as well as their body language indicated to the researcher that both of them were competent. Only on the last day at work (the researcher's final presentation to the managers was made on the final day) the researcher realised that the managers have released a very gifted young worker, as the low experienced worker (the researcher picked this up immediately when one of the managers referred to this worker by a Sinhalese nickname, which approximately translate to "workhorse" in English). The researcher realised that the difference between the -1 level and +1 level of her noise factor was not what she wanted. By then, it was too late to conduct another major experiment!

9.6.3.3. Workers' Tacit Knowledge

When the main experiment was in progress (and also during the preliminary experiment that preceded) the two workers would often say "these machine settings are not ideal for a good finish, but I will try my best to give you the best finish I can".⁷⁵ The researcher observes that the workers bring the tacit knowledge into play when they are confronted with a different machine setting to upset the researcher's plans (the researcher assumed

⁷⁵ The settings the workers referred to were the control factor settings: the SPI adjuster screw, presser foot pressure, and the feed-dog height (see section 5.5.1 for details).

that a skilled worker and a not so skilled worker in a natural setting can be approximated by N1 years of experience and N2 years of experience respectively). The bottom Line was that neither of the two workers wanted to produce ordinary work as they are not used to doing so. The younger worker even tried harder to pursue perfection as she thought that she is pitted against the older worker who was 15 years her senior.

However, the operators contention that some factor combinations (machine settings) are not ideal for a good finish but they would nonetheless try their best, suggested that the researcher's logic in designing the experiment has been correct. The logic of the researcher's RPD experiment was that there exists an optimum machine setting that results in the least amount of difficult sewing manoeuvres (hence less variability of the response variables such as the back coverage) to overcome different types of fabric, machine conditions (presser foot conditions), and handling conditions.

Even though designing an ideal experiment was not a requirement for this research, knowing that the researcher's experimental logic has been correct provided great satisfaction to the researcher, because not only is she satisfied that she has made a theoretical contribution to the field of quality and operations management (see section 9.4.1), but she also knows that she has set up the right experiment for the case study organisation to capitalise on.

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APPENDICES

- APPENDIX A: Survey Questionnaire (English and Sinhala)
- APPENDIX B: Certificate Received by the Candidate for the Best Paper Award
- APPENDIX C: Massey University Human Ethics Approval – Low Risk
- APPENDIX D: Results of the Preliminary Experiment Conducted
- APPENDIX E: Important Correlation Matrices and Frequency Distribution Plots of the Measures
- APPENDIX F: The Financial Impact of the QI Experiment
- APPENDIX G: The Combined Array for the Response Surface Approach
- APPENDIX H: The Results of the Main Experiment for Response Variables of Secondary Importance
- APPENDIX I: A Sample of Quality Tools Collected from the Factory Belonging to the Case Study Organization

APPENDIX A: SURVEY QUESTIONNAIRE (ENGLISH AND SINHALA)



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Dear Sir/Madam

Data collection for a PhD Study on Manufacturing Management

I am an engineering graduate from the University of Peradeniya and pursuing my PhD in Technology at Massey University, New Zealand. I need data to test certain production management theories I developed and therefore I solicit your support by way of responding to my attached questionnaire. Do please read the instructions in this cover letter before you respond to the questionnaire.

It will take about 20-25 minutes of your valuable time to answer all the questionnaire items. Please attempt to answer all the items. **However, if you are unsure about a particular item in this questionnaire, please leave that item blank.**

This questionnaire consists of two parts. **Part A** of the questionnaire covers general information about you while **Part B** covers 40 statements related to production environment of your company. Your responses will be anonymous. All information provided by you will be treated with the utmost confidentiality and adhere to Massey University Ethics Committee Policies and Procedures. I plan to send a summary of my findings to your department in due course.

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the Massey University's Human Ethics Committees. I am responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you wish to raise with someone other than me, please contact Professor John O'Neill, Director (Research Ethics), telephone +64 6 350 5249, e-mail humanethics@massey.ac.nz. You can also contact my supervisors Dr. Nihal Jayamaha, e-mail N.P.Jayamaha@massey.ac.nz or Associate Professor (Dr) Nigel Grigg, e-mail N.Grigg@massey.ac.nz.

Thanking you in advance for your support.

Yours Truly

.....

Pramila Gamage

PhD Candidate

School of Engineering and Advanced Technology

MasseyUniversity,Private Bag 11222, Palmerston North

New Zealand.

Email: P.Gamage@massey.ac.nz, pramila.gamage@gmail.com

Part A – General Information

Please tick (✓) the appropriate box for each item in this section.

1. Gender Male Female

2. You belong to the following age category:

18-21 years

22-25 years

26 -30 years

31 -40 years

Over 41 years

3. You have worked in the apparel industry for

Less than 2 years

Between 2 -5 years

Between 5 -10 years

More than 10 years

4. Your highest educational qualification is

GCE (O-Level)

GCE (A-Level)

Bachelor's Degree

Post Graduate Degree

Other educational and professional qualifications (please state):.....

.....

5. You belong to the following employment category

Manager Assistant Manager Executive

Staff Supervisor Team Leader

Team member AQL QC

Cutting

Part B

Please indicate your level of agreement by ticking (✓) the most appropriate box to each statement in this section.

		Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	Our process development methods are highly effective.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2	Our product development methods are highly effective.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3	The processes and tasks in my company are clearly standardised (standard work sheet, SMV etc).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4	Our company's improvement tasks are embedded in the regular and everyday activities of employees.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5	We maintain our plant in a clean and orderly manner.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6	We have achieved significant progress in reducing the manufacturing cycle time of our products over the last 2 years.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7	Our company uses on-going assessments to ensure that the organisation's structure and infrastructure support the corporate and departmental strategies.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8	Our company designs the physical layout of the plant to improve the material flow.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9	We rarely get complaints from our customers about product quality and/or delivery performance.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10	We can determine the optimum (best) process setting for each factor (e.g. Stitches Per Inch (SPI), seam width, sewing allowances) by changing one factor at a time.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
11	The employees in our plants are rewarded appropriately for improvement suggestions, taking into account the nature of the problem and the solution/s provided.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
12	We try to make our manufacturing processes perform consistently under varying operating conditions (e.g. different product, different shift/operator).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
13	In cases where product or process specifications are used, we use the term 'quality' to mean little or no deviation from the target value.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
14	We believe that the ultimate judge of our products and services is our customers.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
15	The mechanisms used to enable continuous improvement efforts (e.g. training, teamwork) in our company are monitored and/or further developed.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
16	Our managers lead by example, becoming actively involved in design and implementation of improvements in all forms (e.g. product, processes, team capability building).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

		Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
17	People in our company use appropriate tools (e.g. check sheet, fishbone diagram) and techniques to support continuous improvement.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
18	We maintain long term relationships with our suppliers.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
19	In cases where tolerance limits use for product or process, we view any deviation from the target value as a loss to our external customers (e.g. having to discard the product earlier than expected).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
20	In cases where tolerance limits use for product or process, we view any deviation from the target value as a loss to our company (e.g. loss of goodwill, more rework or scrap, loss of customer loyalty).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
21	We attempt to continuously reduce the change-over time (e.g. Quick-Change-Over).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
22	Everyone in our company understands their department's strategies, goals and objectives.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
23	We use pull production system with signal (e.g. Kanban) for production control (controlling the process flow).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
24	Our organisation has a system that enables learning through experience.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
25	We use visual control systems (e.g. Andon lights) to indicate problems in the production floor.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
26	Our unit cost of production is lower than that of our competitors.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
27	We try to make our products perform consistently under varying user conditions (e.g. washing, drying, and ironing).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
28	We have achieved significant progress in reducing the percentage of internal scrap and rework over the last 2 years.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
29	We believe that quality cannot be achieved only through inspecting/controlling the production process.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
30	We maximise the effectiveness of machine and equipment through a planned predictive and preventive maintenance programme.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
31	We use standardised methods to identify problems or defects in the process and the product (compare with standard layout, WIP etc).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
32	Our processes support the strategic objectives of our organisation.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
33	We use cross-functional teams to solve problems.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
34	Our company develops exceptional individuals and teams who thoroughly understand their work, and coach others how activities are organised and done as per the "MOS Way".	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
35	We have made significant improvements in reducing new product development time over the last 2 years.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

		Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
36	Our managers reinforce positive behaviour, not by punishing mistakes but by encouraging learning from them.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
37	We map the flow of physical goods and information of the whole organisation to achieve improvements.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
38	The risk and uncertainty that the final product will not meet customer requirements has been reduced by our company over the last 2 years.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
39	Our employees become multi-skilled in operations through frequent job rotation.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
40	Our company provides opportunities for my growth and development.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>



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ප්‍රිය මහත්මයා/ මහත්මිය/ මිය

නිෂ්පාදන කළමනාකාරිත්ව ආචාර්ය උපාධි අධ්‍යයනය සඳහා දත්ත එක්රැස් කිරීම

මම ප්‍රධානියෙක් විශ්වවිද්‍යාලයේ ඉංජිනේරු උපාධිධාරිණියක වන අතර දැනට මැසී විශ්වවිද්‍යාලයෙහි (Massey University, New Zealand) ඉංජිනේරු ආචාර්ය උපාධිය හදාරන්නෙමි. මා හට නිෂ්පාදන කළමනාකරණය පිළිබඳ නියායයන් කිපයක් පරීක්ෂා කිරීම සඳහා දත්ත උවමනාකර ඇත. ඒ සඳහා අවශ්‍ය ප්‍රශ්නාවලියක් මා විසින් නිමවා මේ ලිපිය සමග අමුණා ඇත.

ඔබගේ වටිනා කාලයෙන් මිනිත්තු 20 - 25 ක කාලයක් වැයකොට මෙම ප්‍රශ්නාවලියට පිළිතුරු ලබාදෙන ලෙස කාරුණිකව ඉල්ලා සිටින්නෙමි. සියළුම ප්‍රශ්න සඳහා ඔබගේ උපරිම දායකත්වය ලබාදෙන ලෙසත්, ඔබට අවිනිශ්චිත හෝ සැකසහිත ප්‍රශ්න ඇත්නම් එම ප්‍රශ්න හිස්ව තබන ලෙසත් කාරුණිකව ඉල්ලා සිටින්නෙමි.

මෙම ප්‍රශ්නාවලිය කොටස් දෙකකින් (02) සමන්විතව වේ. 'අ' කොටස ඔබගේ සාමාන්‍ය කරුණු ආවරණය කරනු ලබන අතර 'ඕ' කොටස ඔබගේ ආයතනයේ නිෂ්පාදන වාතාවරණය පිළිබඳ ප්‍රකාශන 40 කින් සමන්විතවේ. ඔබගේ ප්‍රතිචාර දැක්වීම නිරන්තරිත වන අතර ඔබ විසින් ලබාදෙන සියළුම තොරතුරුවල උපරිම රහස්‍යය භාවය සුරකින අතර එය මැසී විශ්වවිද්‍යාලයේ සඳාචාර කාරකසභා ප්‍රතිපත්ති හා ක්‍රියාපටිපාටිවලට අනුකූලව පවතින්නේය.

යථාකාලයේදී මෙම පරීක්ෂණය මගින් සොයාගනු ලබනදෙහි සාරාංශය ඔබ හට ඔබගේ දෙපාර්තමේන්තුව හරහා ලැබීමට සලස්වන්නෙමි.

මෙම ව්‍යාපෘතිය සමීයුරු පරීක්ෂණය (peer review) මගින් පරීක්ෂාකොට අඩු අවදානම් සහිතව විශ්වයකොට ඇත. ඒ හෙයින් මෙම ව්‍යාපෘතිය මැසී විශ්වවිද්‍යාලය මානව සඳාචාර කාරකසභාව මගින් පරීක්ෂා කිරීමට අවශ්‍ය වී නැත. මම මෙම පරීක්ෂණයේ ආචාරධර්ම පිළිබඳ සම්පූර්ණ වගකියන්නෙමි. ඔබ හට මා මෙම පරීක්ෂණය සිදුකරන ආකාරය පිළිබඳ කිසිදු හැට්ටවක් මා හැර වෙනත් අයකු සමග සාකච්ඡා කිරීමට බලාපොරොත්තු වන්නේනම් කාරුණිකව මහාචාර්යය ජෝන් ඕ'නෙයිල් මහතා (Professor John O'Neill) අධ්‍යයනික (Research Ethics), දුරකථන +64 6 350 3 249, විද්‍යුත් තැපෑල humanethics@massey.ac.nz හරහා සම්බන්ධ කරගත හැක. එමෙන්ම මාගේ අධීක්ෂක වරුන්වන ආචාර්යය නිහාල් ජයමහ, විද්‍යුත් තැපෑල N.P.Jayamaha@massey.ac.nz හෝ මහාචාර්යය නයිජල් ග්‍රීන්, විද්‍යුත් තැපෑල N.Grigg@massey.ac.nz හරහා සම්බන්ධ කරගත හැක.

ඔබගේ සහයෝගයට මාගේ හදවිටි ස්තූතිය.

මිව විශ්වාසී,

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ප්‍රමිලා ගමගේ

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'අ' කොටස - සාමාන්‍ය කරුණු

කරුණාකර මෙම කොටසෙහි ඇතුළත් කරුණු වලට සුදුසු කොටුවෙහි හරි (✓) ලකුණ යොදන්න.

1. ස්ත්‍රී/පුරුෂ භාවය ස්ත්‍රී පුරුෂ

2. ඔබ අදාළ වනුයේ පහත කුමන වයස් කාණ්ඩයටද?

- අවුරුදු 18 - 21
- අවුරුදු 22 - 25
- අවුරුදු 26 - 30
- අවුරුදු 31 - 40
- අවුරුදු 41 ට වඩා වැඩි

3. ඔබ ඇඟළුම් කර්මාන්තයේ නියැලී සිටින්නේ,

- අවුරුදු 2කට වඩා අඩු කාලයක සිට
- අවුරුදු 2න් 5ත් අතර කාලයක සිට
- අවුරුදු 5න් 10ත් අතර කාලයක සිට
- අවුරුදු 10ට වඩා වැඩි කාලයක සිට

4. ඔබගේ ඉහළම අධ්‍යාපන සුදුසුකම් වනුයේ,

- අ. පො. ස. සාමාන්‍ය පෙළ
- අ. පො. ස. උසස් පෙළ
- සරසවි ප්‍රථම උපාධිය (උ.දා. විද්‍යාවේදී, ශාස්ත්‍රවේදී)
- පශ්චාත් උපාධිය

වෙනත් අධ්‍යාපන හා වෘත්තීමය සුදුසුකම් (කරුණාකර මෙහි සඳහන් කරන්න)

.....

5. ඔබ අදාළ වනුයේ පහත කුමන රැකියා කාණ්ඩයටද?

- කළමනාකරු සහය කළමනාකරු විධායක නිලධාරී
- කාර්යය මණ්ඩල අධීක්ෂක කණ්ඩායම් නායකා
- කණ්ඩායම් සමාජීකා AQL QC

‘බී’ කොටස

කරුණාකර මෙම කොටසෙහි ඇතුළත් කරුණුවලට ඔබගේ එකඟත්වයට අදාලවන වඩාත් සුදුසු කොටුවෙහි හරි (√) ලකුණ යොදන්න.

		නොහොත්ම එකඟ නොවේ	එකඟ නොවේ	තරමක් දුරට එකඟ වේ	මධ්‍යස්ථ අදහසක පිටි මදක් එකඟ වේ	එකඟ වේ	සම්පූර්ණයෙන් එකඟ වේ
1	අපගේ නිෂ්පාදන ක්‍රියාවලිය දියුණු කිරීමට යොදාගනු ලබන ක්‍රමවල ස්ඵලතාවය ඉතා ඉහළය.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2	අපගේ නිෂ්පාදන භාණ්ඩ දියුණු කිරීමට යොදාගනු ලබන ක්‍රමවල ස්ඵලතාවය ඉතා ඉහළය.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3	අප ආයතනයේ නිෂ්පාදන ක්‍රියාවලිය (process) හා කර්තව්‍යයන් (task) පැහැදිලිව ප්‍රමිතිගත කර ඇත (standard work sheet, SMV etc.).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4	අප ආයතනයෙහි සංවර්ධනය සඳහා වූ කර්තව්‍යයන් සේවක/ සේවිකාවන්ගේ දෛනික වැඩකටයුතු වල අන්තර්ගත කර ඇත.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5	අපි අපගේ කර්මාන්තශාලාව පිරිසිදුව හා ක්‍රමවත්ව පවත්වාගෙන යන්නෙමු.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6	අප පසුගිය අවුරුදු 2ක කාලය තුළ, නිෂ්පාදන භාණ්ඩයන්හි මුළු නිෂ්පාදන කාලය අවම කිරීමෙහිලා සැලකිය යුතු ප්‍රගතියක් ලබා ඇත.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7	අප ආයතනයේ ව්‍යුහයෙන් සහ යටිතල පහසුකම් තුළින් ආයතනයෙහි උපායමාර්ගවලට සහයෝගය ලැබෙන්නේදැයි නිරතුරුව සොයා බලයි.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8	අපගේ ආයතනය එහි යන්ත්‍රෝපකරණවල භෞතික සැලැස්ම (physical layout) සකස් කරනුයේ ද්‍රව්‍යය ගලායාම (material flow) උපරිම වන පරිදිය.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9	අපගේ නිෂ්පාදනවල ‘තත්වය’ (quality) සහ/ හෝ ඒවා බෙදාහැරීමේ ක්‍රියාදාමයට පැමිණිලි ලැබෙනුයේ කලාතුරකිනි.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10	අප වරකට එක් සාධකය බැගින් වෙනස් කරමින් අපගේ නිෂ්පාදන කාර්යයාවලියෙහි සාධකවල (උදා. SPI , මැනුම්වාසි) වඩාත් උචිත අගයන් සොයා ගනියි.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
11	අප ආයතනයේ සේවක/ සේවිකාවන් විසින් ආයතනයේ වැඩිදියුණුව සඳහා ලබාදෙන්නාවූ යෝජනාවල ස්වාභාවය හා ඒවායින් ගැටළු නිරාකරණයට දක්වන දායකත්වයට අනුව ඔවුන්ට පාරිභෝගික ප්‍රදානය කරයි.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
12	අප විවිධවූ ක්‍රියාකාරී තත්ව (උදා. විවිධ නිෂ්පාදන, විවිධ වැඩමුරු, ක්‍රියාකරුවන්ගේ, ක්‍රියාකරුවන්ගේ) යටතේ වුවද ආයතනයේ නිෂ්පාදන ක්‍රියාවලිය ස්ථිරව පවත්වාගෙන යාමට උත්සහ දරයි.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
13	නිෂ්පාදන භාණ්ඩ හා නිෂ්පාදන ක්‍රියාවලියෙහි විශේෂ නියාමක (specification) භාවිතා කරන අවස්ථාවලදී, අප ‘තත්වය’ (quality) යන වචනයෙන් අදහස් කරනුයේ ඉලක්ක කරන අගයේ කිසිදු අපගමනයක් / වෙනසක් (deviation) නොමැති වීමය.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
14	අපි විශ්වාස කරනවා පාරිභෝගිකයා අපගේ නිෂ්පාදිත භාණ්ඩ හෝ සේවාවල අවසාන කීරකයා ලෙස.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
15	අප ආයතනය අඛණ්ඩ දියුණුව පවත්වාගෙන යාමට දරණ උත්සහයන්ට යොදන උපක්‍රම (උදා. සේවා පුහුණු වැඩසටහන්, කණ්ඩායම් ක්‍රියාකාරකම්) අධ්‍යයනය කිරීම සහ/ හෝ තවදුරටත් වැඩිදියුණු කිරීමට ක්‍රියා කරයි.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

		කොහොත්ම එකඟ නොවේ	එකඟ නොවේ	තරමක් දුරට එකඟ වේ	මධ්‍යස්ථ ඇඟවුමක් පිළිබඳව එකඟ වේ	එකඟ වේ	සම්පූර්ණයෙන් එකඟ වේ
16	අප කළමනාකාරිත්වය ආයතනයෙහි දියුණුවට අවශ්‍ය සැලසුම් නිර්මාණය හා ක්‍රියාවට නැංවීමේලා සක්‍රීයව සම්බන්ධ වෙමින් ආදර්ශවත් නායකත්වයක් ලබාදෙයි.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
17	අප ආයතනයෙහි පුද්ගලයන් එහි අඛණ්ඩව දියුණුවට යෝග්‍යවූ උපකරණ හා තාක්ෂණය භාවිතා කරයි (උද. මාපකටු සටහන, check sheet).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
18	අපි සැපයුම්කරුවන් (suppliers) සමඟ දීර්ඝකාලීන සම්බන්ධතා පවත්වාගෙන යන්නෙමු.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
19	නිෂ්පාදන භාණ්ඩ හා නිෂ්පාදන සඳහා අප සහන සීමා (tolerance limits) භාවිතා කලද, ඉලක්ක කරන අගයෙන් (target value) කිසියම් හෝ ප්‍රමාණයක අපගමනයක් / වෙනසක් (deviation) පාරිභෝගිකයාට පාඩුවක්/ අලාභයක් ලෙස අපි දකිමු.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
20	නිෂ්පාදන භාණ්ඩ හා නිෂ්පාදන ක්‍රියාවලි සඳහා අප සහන සීමා (tolerance limits) භාවිතා කලද, ඉලක්ක කරන අගයෙන් (target value) කිසියම් හෝ ප්‍රමාණයක අපගමනයක් / වෙනසක් (deviation) අපගේ ආයතනයට පාඩුවක්/ අලාභයක් ලෙස අපි දකිමු.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
21	අපි එක් නිෂ්පාදනයකින් වෙනත් නිෂ්පාදනයකට මාරුවීමට ගතවන කාලය (change-over-time) අවම කිරීමට අඛණ්ඩව උත්සහ දරන්නෙමු. (උද. quick change-over).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
22	අපගේ ආයතනයේ සිටින සියළුමදෙනා ඔවුන්ගේ අදාල අංශයේ ක්‍රමෝපායන්, අභිමතාර්ථ සහ පරමාර්ථ වටහාගෙන සිටියි.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
23	අප නිෂ්පාදන ක්‍රියාවලියේ ගලායාම් පාලනය කිරීම සඳහා සංඥා (උද. කාන්බාන්) සහිත 'පුල් ප්‍රොඩක්ෂන්' (pull production) ක්‍රමය භාවිතා කරයි.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
24	අප ආයතනයෙහි අන්දැකීම් තුලින් ඉගෙන ගතහැකි ක්‍රියාපිළිවෙලක් පවතී.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
25	අපි නිෂ්පාදන බිමෙහි (production floor) පවතින ගැටළු පෙන්වා දීමට දෘෂ්‍ය පාලන පද්ධතියක් (උද. ඇන්ඩන් බල්බ්) භාවිතා කරන්නෙමු.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
26	තරඟකාරී ආයතන හා සැසඳූ කල අපගේ නිෂ්පාදන භාණ්ඩයන්හි ඒකක මිල පහල අගයක පවතී.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
27	පාරිභෝගිකයාගේ විවිධාකාරවූ භාවිතාවන් (උද. වියළීම, සේදීම්, මැදීම්) යටතේ වුවද අපගේ නිෂ්පාදිත භාණ්ඩතුලින් ඔහු බලාපොරොත්තුවන ආකාරයෙන් අවශ්‍යතාවයන් සැපිරීමට අප උත්සහ දරයි.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
28	පසුගිය අවුරුදු 2ක කාලය තුළ , අභ්‍යන්තර නාස්කි හා අපතේයාම් අඩුකිරීමේ සැලකිය යුතු ප්‍රගතියක් අප ලබා ඇත.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
29	අපි විශ්වාස කරනවා පිරික්සීමෙන් සහ/ හෝ පාලනය කිරීමෙන් පමණක් නිෂ්පාදන භාණ්ඩ හා ක්‍රියාවලියේ 'තත්වය' (quality) ඉහල නංවාගත නොහැකි බව.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
30	අප ආයතන සැලසුම්සහගත තඩත්තුව තුලින් යන්ත්‍රෝපකරණවල උපරිම සඵලතාවය (effectiveness) ලබා ගනී.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
31	අපගේ නිෂ්පාදන භාණ්ඩ හෝ නිෂ්පාදන ක්‍රියාවලියේ පවතින ගැටළු හෝ අඩුපාඩු ප්‍රමිතිගත ක්‍රමවේද තුලින් හඳුනා ගනී (උද. සම්මත හෞතික සැලැස්ම , WIP යනාදිය හා සැසඳීමෙන්).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

		කොතෙත්ම එකත තොවේ	එකත තොවේ	තරමක් දුරට එකත වේ	මධ්‍යස්ථ අදහසක යිටී	මදක් එකත වේ	එකත වේ	සම්පූර්ණයෙන් එකත වේ
32	අපගේ නිෂ්පාදන ක්‍රියාවලිය ආයතනයේ ක්‍රමෝපාය වලට සහයවේ.	<input type="checkbox"/>						
33	අප ආයතනය ඇතිවන ගැටළු විසඳීම සඳහා විවිධ මට්ටම්වල සේවක/ සේවිකාවන්ගෙන් සැලසුම්ලත් කණ්ඩායම් යොදා ගනී.	<input type="checkbox"/>						
34	අප ආයතනය MOS ක්‍රමවේදයට අනුව, තම කාර්යය මැනවින් වටහා ගනිමින් අන් අයට කියාදියහැකි, දෘෂ්‍ය පුද්ගලයන් හා කණ්ඩායම් බිහි කරයි.	<input type="checkbox"/>						
35	අපි පසුගිය අවුරුදු 2ක කාලය තුළ, නව විලාසිතා නිෂ්පාදනයට හඳුන්වා දීමට ගතවන කාලය අවම කිරීමේභිලා සැලකිය යුතු ප්‍රගතියක් ලබා ඇත.	<input type="checkbox"/>						
36	අපගේ කළමනාකාරිත්වය වැරදිවලට දඬුවම් කිරීමට යොමු වනවාට වඩා වැරදි වලින් ඉගෙන ගැනීමට අනුබල දෙමින් කටයුතු කරයි.	<input type="checkbox"/>						
37	අප ආයතනයේ දියුණුව සඳහා සියළුම නිෂ්පාදන ද්‍රව්‍ය හා දත්ත ගලායාම පිතියම්ගත කරයි.	<input type="checkbox"/>						
38	අපි පසුගිය අවුරුදු 2ක කාලය තුළ, අවසන් නිෂ්පාදිත භාණ්ඩ මගින් පාරිභෝගිකයාගේ අවශ්‍යතා සපිරීමේදී ඇතිවිය හැකි අවධානම් හා අවිනිශ්චිතතාවය අඩුකිරීමේභිලා සුවිශේෂී දියුණුවක් ලබා ඇත.	<input type="checkbox"/>						
39	අපගේ සේවක/ සේවිකාවන් යෙදෙන කාර්යයන් නිරතුරු වෙනස් කිරීම කුලින් ඔවුන් විවිධ කාර්යයන්හි දෘෂ්‍යතාවයට පත්ව ඇත.	<input type="checkbox"/>						
40	මාගේ ආයතනය මාගේ වැඩි දියුණුවට අත්තින් සහ අවස්ථාව සලසා දෙයි.	<input type="checkbox"/>						

**APPENDIX B: CERTIFICATE RECEIVED BY THE CANDIDATE FOR THE
BEST PAPER AWARD**

ANZAM Operations, Supply Chain and
Services Management Symposium 2014

Best Paper Award

Testing a theoretical model integrating Taguchi's quality philosophy and Lean philosophy -
an empirical study involving a large apparel manufacturer

awarded to

Co-authors

Pramila Gamage
Nihal P Jayamaha
Nigel P Grigg
Manjula Nanayakkara



3 / 07 / 2014

Professor Tava Olsen

Parts of Auckland Chair in Logistics and Supply Chain Management
Academic Director, Centre for Supply Chain Management
The University of Auckland Business School



ANZAM
AUSTRALIAN & NEW ZEALAND
ACADEMY OF MANAGEMENT



**THE UNIVERSITY
OF AUCKLAND**
BUSINESS SCHOOL

APPENDIX C: MASSEY UNIVERSITY HUMAN ETHICS APPROVAL – LOW RISK



MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

3 October 2012

Pramila Gamage
c/o School of Engineering and Advanced
Technology
PN321

Dear Pramila

Re: Incorporation of Taguchi Methods in Lean Manufacturing

Thank you for your Low Risk Notification which was received on 17 September 2012.

Your project has been recorded on the Low Risk Database which is reported in the Annual Report of the Massey University Human Ethics Committees.

The low risk notification for this project is valid for a maximum of three years.

Please notify me if situations subsequently occur which cause you to reconsider your initial ethical analysis that it is safe to proceed without approval by one of the University's Human Ethics Committees.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

A reminder to include the following statement on all public documents:

"This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Professor John O'Neill, Director (Research Ethics), telephone 06 350 5249, e-mail humanethics@massey.ac.nz".

Please note that if a sponsoring organisation, funding authority or a journal in which you wish to publish requires evidence of committee approval (with an approval number), you will have to provide a full application to one of the University's Human Ethics Committees. You should also note that such an approval can only be provided prior to the commencement of the research.

Yours sincerely

John G O'Neill (Professor)
**Chair, Human Ethics Chairs' Committee and
Director (Research Ethics)**

cc Dr Nihal Jayamaha
School of Engineering and Advanced
Technology
PN321

Prof Don Cleland, HoS
School of Engineering and Advanced
Technology
PN321

Massey University Human Ethics Committee
Accredited by the Health Research Council

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E humanethics@massey.ac.nz animalethics@massey.ac.nz gtc@massey.ac.nz
www.massey.ac.nz

Note that this report has been written in first person because it is a report that was produced for the case study organisation.

APPENDIX D: RESULTS OF THE PRELIMINARY EXPERIMENT CONDUCTED

Title: Design and Analysis of a Smaller Scale Robust Design of Experiment as a Forerunner to the Final Experiment to Understand the Sewing Process Better

Experimenter: Pramila Gamage

Location: Pallekelle, Kandy, Sri Lanka

Date: 2nd November 2013

D.1. Introduction

Based on my experience to date, I observe that there are several opportunities to use design on experiments (DoE) in conjunction with the standard tools that you use for problem solving. DoE is not a difficult science for you to comprehend, if the right tools are introduced to you. Some of the data analysis pertaining to this report belongs to mainstream DoE techniques, as opposed to Taguchi methods. However, the procedures used in setting-up of the experiment will not change when we use Taguchi methods in the main experiment.

All experiments involve an element of risk of failure. However, a failed experiment does not mean that the experimenters do not learn anything from the experiment. It is the converse that is true. The success of a variation reduction sewing experiment, based on DoE, depends on many factors. These include the QI team being able to: (a) identify the potential factors that can be manipulated to optimise the sewing process, (b) identify from where the noise is coming from, (c) identify the number of levels the factors should be manipulated and the specific levels chosen (the gap between the levels should be carefully chosen), (d) have a satisfactorily precise measurement system (the operators and the equipment being used to take measurements), (e) ensure that the sewing process does not get affected by special causes (e.g. incorrect machine setting, defective machine parts).

This report involves studying the stitch density variability of a different product (ladies brief style # 12702) than the one we are working on, in regards to the back coverage. The question (I acknowledge that this question is not a critical question in the product concerned) in this report, which involves finding a solution through a smaller experiment, is as follows:

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How could we keep the mean stitch density in the leg-hem area of the brief as close as possible to the target level of 17 stitches per inch (17 SPI)?

D.2 Objectives

The objectives of this preliminary experiment are as follows:

- i. To demonstrate to the QI team how to conduct a statistically designed experiment to tackle a QI problem, and how to interpret Minitab 16 graphical outputs.
- ii. To show how Lean tools can be used in setting up an experiment.
- iii. To identify any possible two factor interactions and explain to the QI team (if such two-way interactions were found to exist) how to interpret a two-way interaction and what it means operationally.
- iv. To estimate the time taken to change each control factor and noise factor.
- v. To identify hard to change factors.
- vi. To find out how many pieces of garments an operator needs to sew at the beginning (warmup) before she gets her usual speed and rhythm.
- vii. To observe how variable the SPI count becomes along the leg hem contour of the garment (both sides and the back), and determine how many measurements need to be taken per garment to capture the quality characteristic “stitch density” of the leg hem operation.

D.3. Materials and Methods

The following material, machinery, equipment, and personnel were involved in the experiment:

- 42 semi-finished pieces garments of style # 12702 (although only 32 pieces are involved in the experiment, 10 extra have been used for work study purposes)

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(e.g. to estimate time taken to change factor settings, pieces to sewed to warm-up to the task).

- 1 sewing machine
- Brand new presser foot and a worn out presser foot
- 2 sewing operators (operator 1 – less experienced; operator 2 – very experienced).
- 1 mechanic.
- 1 measuring tape and a marker.
- 1 work study officer and a stop watch.
- Your adviser (Pramila).

D.3.1. Factors and Levels

The QI team identified the following factors (Table D.1) for experimental manipulation. A two-level experiment was deemed adequate because this is a preliminary experiment and the staff is conducting a multifactor experiment for the first time. Essentially, the factors and levels and the method of deciding these—teamwork, brainstorming, cause-and-effect diagram, Pareto analysis—are based on the main experiment that we are planning to conduct.

Table D.1: Factors and Levels Used in the Experiment

Factor Description	Factor Type	Label	Level 1 (-1)	Level 2 (+1)
SPI adjuster screw length	Control	A	20.5 mm	21 mm
Presser foot pressure	Control	B	21 mm	22 mm
Feed-dog height	Control	C	1	4
Fabric type	Noise	D	Low g/m ²	High g/m ²
Presser foot condition	Noise	E	Old	New
Handling techniques (operator experience)	Noise	F	Low Experience	High Experience

D.3.2. Measurement of Stitch Density – The Response Variable

We know that the stitch densities (the SPI counts) become different in different places on the sewing contour of the leg hem. Because we need a single representative figure

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(measurement) as the response for stitch density (the SPI count) to conduct the experiment economically, the QI team was advised by me that the stitch density (the stitch count per inch) for this experiment should be determined by counting the number of stitches per inch along six, one inch long portions (three on the left and three on the right) along the leg hem contour as shown in Figure D.1. A basic graphical plot shall be used to justify the decision to use six measurements.

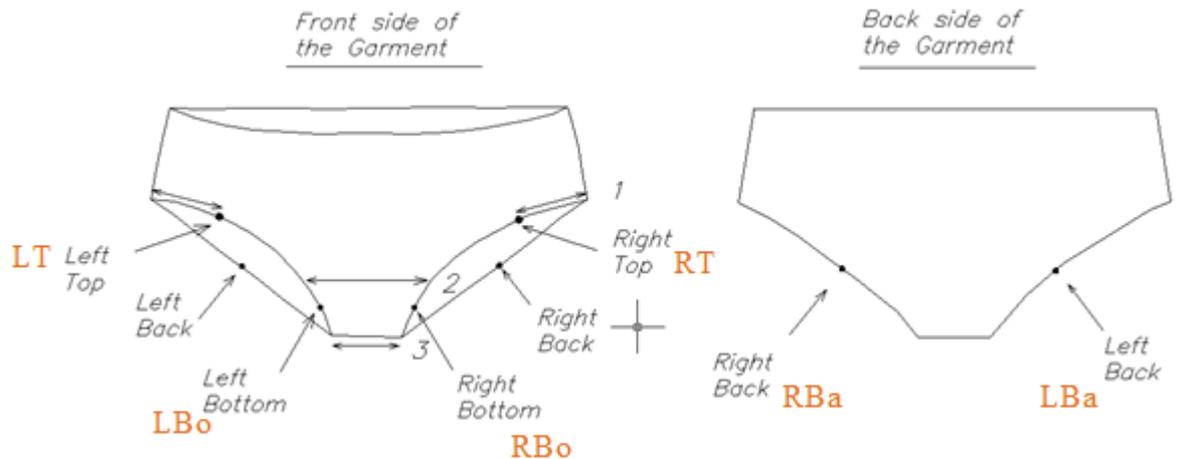


Figure D.1: SPI measurement portions of the leg hem operation for garment style # 12702

Why I advise the QI team to take measurements from 3 locations on each side of the leg hem (hence 6 measurements altogether) are as follows:

- **The reason to take the SPI count at the left bottom and the right bottom (from point 2 to point 3 in sewing contour of leg hem in Figure D.1):** The SPI count at the left bottom or the right bottom area is high. There are three fabric layers in the bottom area of the garment, and hence, the fabric does not get fed easily (it moves slowly). Therefore the SPI count rises, compared to the other areas of the garment.
- **The reason to take the SPI count at the top of the front area (from point 1 to point 2 in sewing contour of leg hem in Figure D.1):** The shape in this area is different, compared to the shape in the back side of the garment. The operator has to sew the top front area slowly, compared to the top area of the backside (the backside in general) of the garment to get the desired shape from the sew

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contour. Thus the SPI count goes up at the top area of the front side relative to the top area of the backside (but not as high as the bottom area).

- **The reason to take the SPI measurement at the back (from point 3 to point 1 in sewing contour of leg hem in Figure D.1):** the back side of the garment has less curvature, resembling almost a straight line. Thus the operator can sew the back portion very easily (the garment gets fed quickly), compared to the other portions. Thus the SPI count becomes lower at the back side, compared to the top and bottom areas of the front side of the garment.

D.3.3. The Design Matrix

Since we agreed that the total time allocated for the study should be limited to 1 working day, the 3 control factors we selected were manipulated at all 8 possible combinations (so an L8 array) of control factor settings, but the 3 noise factors were manipulated only at 4 of the 8 possible combinations, that is, a half fraction of all possible combinations (so an L4 array) to limit the number of sewing trials. This resulted in having only 32 trials (8×4) in the experiment (as opposed to 64 trials that we are going to run in the full experiment). Table D2 shows the 192 (32×6) measurements that were recorded in the 32 trials of the experiment. In Table D.2, I am using colour separation for ease of identifying to which of the 6 sections of the garment a measurement belongs to.

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Table D.2: Crossed Array for the SPI

Control Factor Setting	Control Factors			Noise Factors	The 4 noise conditions			
	A	B	C	D	L4			
				E	-1	+1	-1	+1
F	-1	+1	+1	-1				
1	-1	-1	+1	Left Top (LT)	19	16	16.5	16
2	+1	+1	-1		17	17	17	16
3	-1	+1	+1		16	16	16	16
4	+1	-1	-1		16	16	14	14
5	-1	-1	-1		19.25	18	17	17
6	-1	+1	-1		19	19	17	17
7	+1	-1	+1		14	13.5	13	11
8	+1	+1	+1		15	15	12.25	11.5
1	-1	-1	+1	Right Top (RT)	18.25	15.5	16	15.5
2	+1	+1	-1		18	16	16.5	15
3	-1	+1	+1		15.5	15	19	15.5
4	+1	-1	-1		15.5	16	17.25	13.5
5	-1	-1	-1		18	17	17.25	17
6	-1	+1	-1		18	17.5	18.5	17
7	+1	-1	+1		15	13.5	14	13
8	+1	+1	+1		14.5	13.5	15	12.5
1	-1	-1	+1	Left Bottom Portion (LBo)	18.25	17	17.75	17
2	+1	+1	-1		16	16	18	16
3	-1	+1	+1		17.5	17	18	18
4	+1	-1	-1		16	15	17	16.5
5	-1	-1	-1		18.5	18	18.75	18
6	-1	+1	-1		18	18.25	20	19
7	+1	-1	+1		15	15.25	17	14.25
8	+1	+1	+1		15	14.5	15.5	16
1	-1	-1	+1	Right Bottom Portion (RBo)	18	17	18	16.5
2	+1	+1	-1		16	15	15.5	15.5
3	-1	+1	+1		17	16	17.5	17
4	+1	-1	-1		14	15	16	15
5	-1	-1	-1		18	18	17.5	17.5
6	-1	+1	-1		18	18.75	18.5	18.5
7	+1	-1	+1		15	15	15	15
8	+1	+1	+1		14.5	14.5	16	13.25
1	-1	-1	+1	Left Back Portion (LBa)	17.25	16	16.25	15
2	+1	+1	-1		16.5	15	17	15
3	-1	+1	+1		17	15	17.5	16
4	+1	-1	-1		14.75	16	15	13.5
5	-1	-1	-1		17.75	17	18	17
6	-1	+1	-1		17.5	16	17.5	17
7	+1	-1	+1		14	13.25	14	12.5
8	+1	+1	+1		14.25	12.5	13.25	12
1	-1	-1	+1	Right Back Portion (RBa)	19.25	16.5	16.5	16.5
2	+1	+1	-1		16.5	15.75	16	17
3	-1	+1	+1		16	15.25	16.25	16.5
4	+1	-1	-1		15.5	15	16	15.25
5	-1	-1	-1		18	17	19	17.5
6	-1	+1	-1		19.5	17.25	19.5	17.25
7	+1	-1	+1		15	13	14.25	14
8	+1	+1	+1		16.5	14	16.25	16

Note: For each outer array factor combination (e.g.1,1,1) the eight runs in the inner array was run in a random order.

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D.4. Results and Discussion

D.4.1 Basic Analysis

Figure D.2 shows measurements corresponding to each of the 6 measurement points (left top, left bottom, left back, right top, right bottom, and right back) for each factor combination shown in Table D.2. This graph shows how variable the measures become for each control factor setting (control factor setting 1, 2,...,8) under the 4 noise conditions (see Table D.2). The positive sign in the circle shows the average value of the 4 measurements corresponding to the 4 noise conditions for each control factor setting.

Looking at the average values (the positive circles) in each section for each control factor setting, we can say that they do not look like the same and therefore our decision to measure 6 locations is reasonable; a statistician would conduct a one-way analysis of variance (one-way ANOVA) to ascertain whether the location factor (this factor has 6 levels: LBa, LBo, LT, RBa, RBo, RT) is significant, based on the F value. One-way ANOVA showed that the location factor is significant ($F = 2.81$, $p = 0.018$) at 5% significance level, thus vindicating our decision to select multiple locations to measure.

Also, Figure D.2 shows that in general, factor settings 7 and 8 are the worst combinations (way off than the desired 17 SPI mark) and factor settings 1 and 2 are average and probably a factor setting such as 5 is (all 3 control factors set at the low level) the best, because all 6 measurements approach the 17 SPI mark on average.

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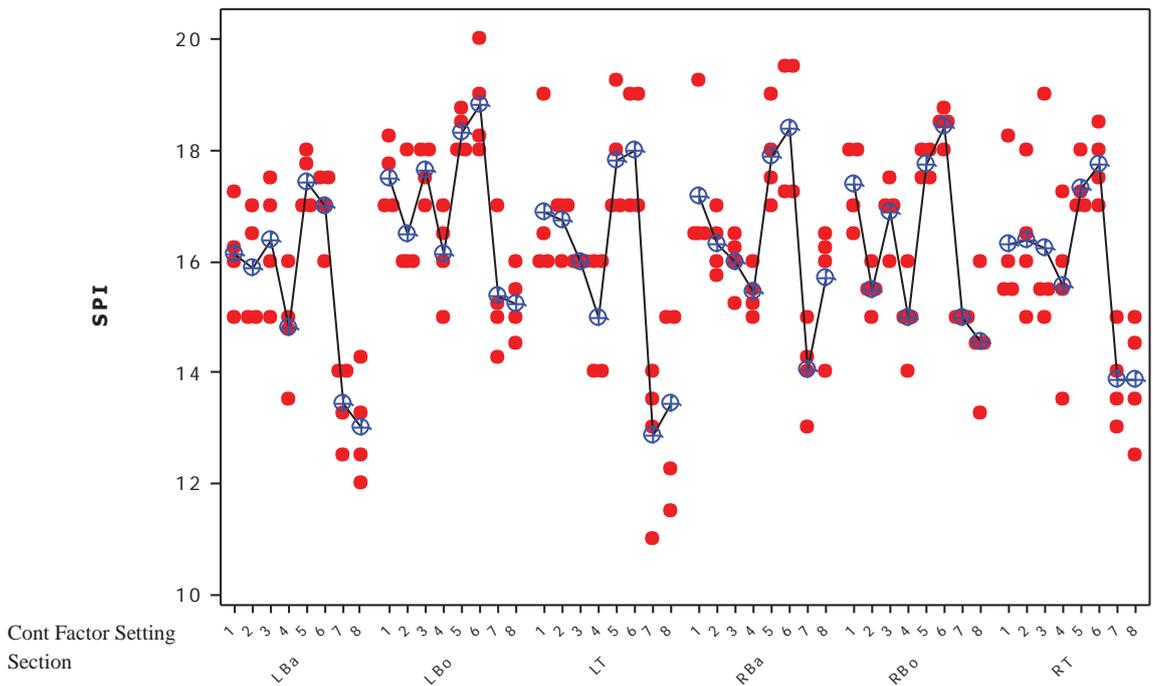


Figure D.2: The individual value plot of SPI at six point of leg hem

Figure D.3 shows the variability of the measurements, based on the operator in the form of a *box plot*. The box plot shows that there is no practically significant difference in measurements between the two operators, implying that the operator experience (treated as a proxy for handling skill) has no effect on stitch density.

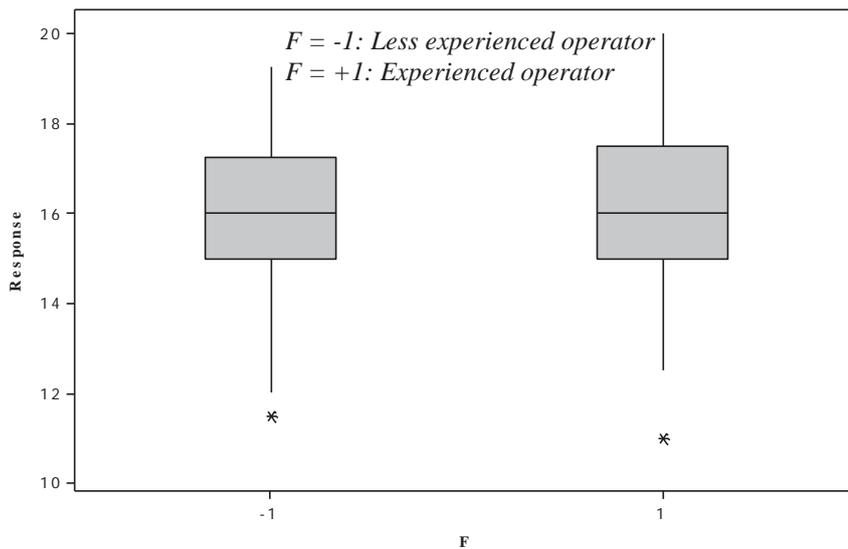


Figure D.3: The box plot of the stitch density variation based on the operator handling skill

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While graphical plots such as D.2 and D.3 are useful, in DoE, the user is provided more easy to understand and versatile graphical plots known factorial plots—the main effects plot and interaction plot—which will be shown next.

Figure D.4 shows the main effects plot of the stitch density. A main effect plot of a factor shows *by how much the response varies on average, when the factor setting is changed from the low setting to the high setting*. Thus a steep line would show a significant (important or influential) main effect while a line that is close to being horizontal shows an insignificant main effect (a statistician would conduct more definitive tests, which are covered later). Figure D.4 shows that factors A, C and D are more important than factors B, E, and F as B, E, and F have near horizontal lines, implying insignificance. In addition, the figure shows that the SPI adjuster screw length (A) and fabric type (D) are the influential control factor and noise factor respectively.

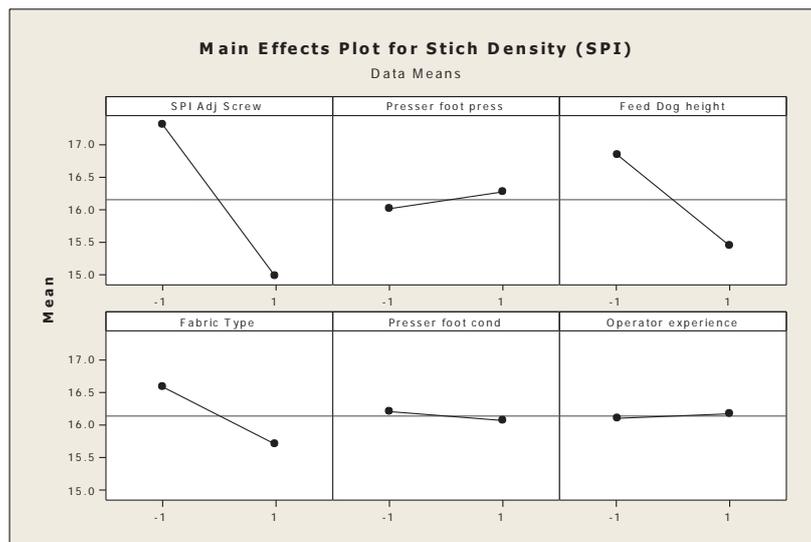


Figure D.4: The main effect plots for all the factors

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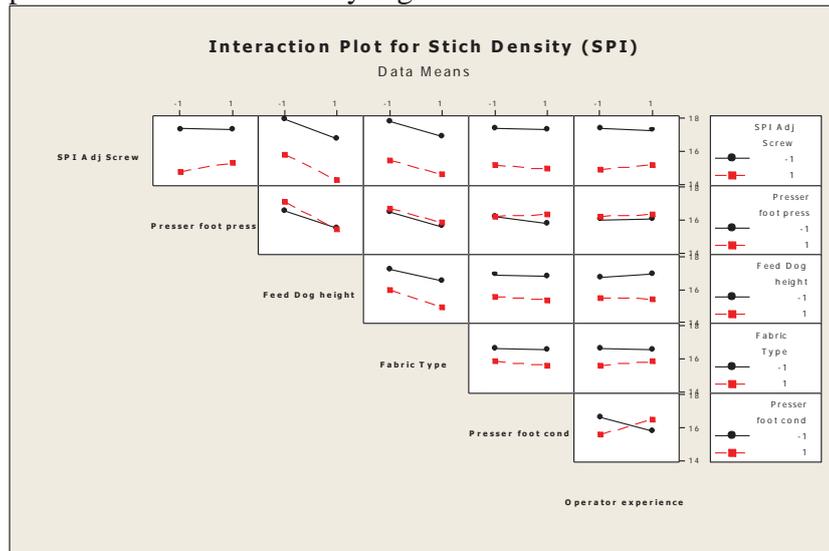


Figure D.5: The two way interaction plots between all the factors

Figure D.5 shows the two-way interaction plots involving all six factors. More specifically, it shows the interactions between control factors, the interactions between noise factors, and the interactions between control and noise factors. The interactions between noise factors in the interaction plot (Figure D.5) do not convey any meaning due to confounding (aliasing).⁷⁶

Figure D.6 shows the structure of aliasing (this figure can be skipped in your first reading as it is, strictly speaking, an advanced concept). Figure D.6 shows that the main effect of a noise factor is confounded with a two-way interaction between noise factors, for example D (fabric type) is confounded with E*F (the two-way interaction between presser foot condition and operator experience). Thus the E*F two way interaction (crossing of the lines in Figure D.5 suggests a sizable interaction) shown in Figure D5 could actually signify the main effect of D (we do not know whether the main effect or the two-way interaction is causing the effect), which of course is significant. Figure D5 shows that there are no important (noticeable) two-way interactions between control factors (the 2 lines are parallel, almost).

Unfortunately, there are no significant two-way interactions between a control factor and a noise factor, *suggesting that manipulating a control factor will not make the*

⁷⁶ This is because we only considered a fraction of noise factor combinations, resulting in the following definition relation: I - D*E*F

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process against the noise factor. This is slightly unfortunate, but that is the nature of an experiment.

A - A*D*E*F	A*B*C - A*B*C*D*E*F
B - B*D*E*F	A*B*D - A*B*E*F
C - C*D*E*F	A*C*D - A*C*E*F
D - E*F	A*B*E - A*B*D*F
E - D*F	A*C*E - A*C*D*F
F - D*E	A*B*F - A*B*D*E
A*B - A*B*D*E*F	A*C*F - A*C*D*E
A*C - A*C*D*E*F	B*C*D - B*C*E*F
A*D - A*E*F	B*C*E - B*C*D*F
A*E - A*D*F	B*C*F - B*C*D*E
A*F - A*D*E	A*B*C*D - A*B*C*E*F
B*C - B*C*D*E*F	A*B*C*E - A*B*C*D*F
B*D - B*E*F	A*B*C*F - A*B*C*D*E
B*E - B*D*F	
B*F - B*D*E	
C*D - C*E*F	
C*E - C*D*F	
C*F - C*D*E	

Notes: The main effects of control factors are confounded with 4-way interactions which literally non-existent (hence the main effects of control factors can be interpreted unambiguously).

A control to noise 2-way interaction (e.g. AD) as well as control to control 2-way interactions are confounded with higher order interactions which are thought to be non-existent (hence the effects of these said 2-way interactions can be interpreted unambiguously)..

Figure D.6: The alias structure

Looking at the main effects plot (Figure D.4), we can say that the mean stitch density is closest to 17 SPI at the following control factor settings:

- SPI adjuster screw length at low (-1) setting (= 20.5mm);
- The feed-dog height also at low (-1) setting (setting 1); the pressure foot pressure has no effect.

The plot also shows that on average, the thinner fabric (low g/m²) gets more stitches than the thicker fabric by about 1 stitch per inch (16.6 SPI approx. versus 15.7 SPI approx.), which is not a practically significant difference.

D.4.2 Advanced Analysis

A very useful graphical plot to analyse the statistical significance of all possible main effects and interactions initially, is the normal plot of effects shown below (Figure D.7). The data points close to the blue line show statistically insignificant effects (the sizes of the effects are small, being close to zero), while the data points away for the

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line (the further the more significant) show significant effects. Thus Figure D.7 confirms our conclusions based on the factorial plots (Figures D.4 and D.5).

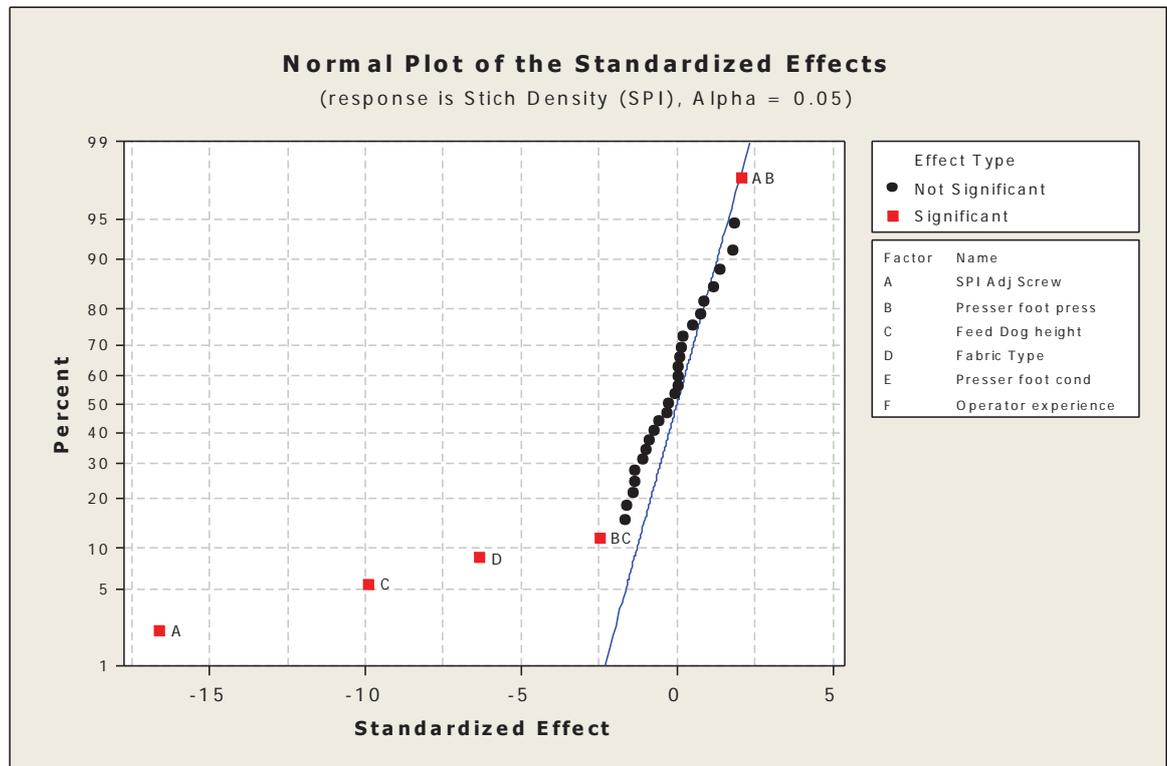


Figure D.7: The normal plot of effects

Figure D.8 shows the results of the *factorial regression analysis*, taking in to consideration that there are only three significant predictors (sources that create a significant impact of the stitch density): A (SPI adj screw), C (Feed-dog height), and D (Fabric type).

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Estimated Effects and Coefficients for Stitch Density (Morse, Barrett, Mayan, Olson, & Spiers) (coded units)						
Term	Effect	Coef	SE Coef	T	P	
Constant		16.147	0.07160	225.53	0.000	
SPI Adj Screw	-2.320	-1.160	0.07160	-16.20	0.000	
Feed Dog height	-1.383	-0.691	0.07160	-9.66	0.000	
Fabric Type	-0.883	-0.441	0.07160	-6.17	0.000	
S = 0.992090 PRESS = 192.995						
R-Sq = 67.69% R-Sq(pred) = 66.30% R-Sq(adj) = 67.17%						
Analysis of Variance for Stitch Density (Morse et al.) (coded units)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	387.618	387.618	129.206	131.27	0.000
SPI Adj Screw	1	258.425	258.425	258.425	262.56	0.000
Feed Dog height	1	91.784	91.784	91.784	93.25	0.000
Fabric Type	1	37.409	37.409	37.409	38.01	0.000
Residual Error	188	185.038	185.038	0.984		
Lack of Fit	4	3.316	3.316	0.829	0.84	0.502
Pure Error	184	181.721	181.721	0.988		
Total	191	572.656				

Figure D.8: Factorial regression results

Figure D.8 shows that collectively, factors A (SPI Adj Screw), C (Feed Dog height), and D (Fabric Type), explain about 2/3 of the variability (R^2 as shown in Figure D.8 = 67.69%) of the 192 measurements (6 measurements taken from 32 pieces of garments). The regression equation can be used to predict the expected (mean) Stitch Density but because the R^2 value is not very high, manipulation of the equation (e.g. deriving contour plots etc., which are not shown in this report) should be undertaken with caution.

Overall, the results show that:

- i. The SPI adjuster screw setting (Factor A) is the most significant control factor—the highest effect (Figure D.7) in and the greatest slope in the main effects plot (Figure D.4).
- ii. It is difficult to achieve a significant degree of robustness as there are no strong two way interactions between control factors and noise factors. However, the control factor setting ‘SPI adjuster screw length’ at 21.0mm and ‘Feed-dog height’ (C) at setting 1, the exact factor combination that the operators have found by trial and error (the mechanics’ support has to be acknowledged), is a

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better control factor setting than any other factor settings considered (the presser foot pressure has no effect).

- iii. The only significant noise factor is the fabric type (Factor D), but practically speaking its effect is very small.
- iv. Partial confounding (see Figure D.6) may have obscured the results.

D.5. Conclusions

Though this experiment, we found that the following factor combination (Table D.3) the factory staff arrived after one month of trial and error was actually the most robust/optimum factor combination relative to the other seven control factor settings. Well done. The experiment also suggests us that the presser foot pressure has no great impact on the outcome (stitch density). One thing the experiment teaches is that DoE could have hasten the decision making, which equates to better utilisation resources using the Lean tools (e.g. the cause-and-effect diagram and Pareto Analysis were important ingredients of this experiment).

I am impressed as much as the staff, on the range of information the experiment provided. I also observe that the staff had no difficulty in interpreting the main effects plots, interaction plots and even the normal plot of effects. All of these graphical plots helped us to understand how the process works and what the optimum factor combination should be.

Table D.3: The Optimum Signal (Design) Factor Combination

Factors Name	Level	Actual Values
SPI adjuster screw length	-1 (Low)	20.5 mm
Presser foot pressure	-1 (Low)	21 mm
Feed-dog height	-1 (Low)	Scale at 1

Table D.4 shows the conclusions reached against each study objective.

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Table D.4. Specific Conclusions on the Objectives of the Study

Objective	Conclusion
(i) Demonstrating to the QI team how to conduct a DoE and use Minitab 16	This was accomplished by explaining every step before, during, and after the experiment.
(ii) Show the utility of Lean tools	Lean tools were an integral part in setting-up the experiment. Brainstorming, cause-and-effect diagram, and the Pareto chart were central to this experiment; so were reliance on graphical tools produced by Minitab 16.
(iii) Identifying and explaining two factor interactions	This was accomplished and the staff understood how to interpret a two-way interaction plot although they did not comprehend what factor aliasing means.
(iv) Estimating the changeover times	The changeover time varied between 8 minutes to 10 minutes from one trial (factor combination) to another.
(v) Identifying hard to change factors	No hard to change factors were found in this experiment. This piece of information is useful in the next experiment (the main experiment).
(vi) Pieces need to be sewed to warm-up!	It was found that an operator gets her usual speed and poise from the very first garment that she sews! Interestingly, the operator experience was not found to cause a significant (Figures D.3 and D.4) effect on the outcome.
(vii) Study how the SPI count varies over the leg hem contour (product style # 12702) and justify taking six places for measurement	Six measurements were taken in each garment (3 sections per side), which was labour intensive, although in the Sri Lankan context, this was not a problem. There was a significant difference in stitch density (the SPI count) at different locations (sections) of the sewing contour on both the left side and the right side of the garment (see Figure D.2 and the associated discussion).

APPENDIX E: IMPORTANT CORRELATION MATRICES AND FREQUENCY DISTRIBUTION PLOTS OF THE MEASURES

This appendix contains two parts. The first part of the appendix depicts two important correlation matrices. The first correlation matrix (Table E.1) is on the correlations between the measures (after parcelling), from which the structural equation modelling (SEM) results can be reproduced (i.e. model fit parameters and parameters for the measurement models and the structural model). The second correlation matrix (Table E.2) is on the correlations between the 4 latent variables of the model.

Note that the correlations between the 4 latent variables in the model (Table E.2) were obtained by conducting confirmatory factor analysis (CFA); these correlations will be exactly equal to the correlations between the latent variables in the hypothesised model (if the analyst was able to find these correlations, one way or the other) because, as mentioned earlier, the CFA model is equivalent to the hypothesised theoretical model (e.g. same goodness-of-fit and same structural coefficients).⁷⁷

The second part of the appendix relates to frequency distribution histograms of the 15 measures. To limit the number of plots, the researcher has selected the best case (the histogram that is closest to a bell curve) and worst case (the histogram that is furthest to a bell curve) only.

⁷⁷ Theoretically, it is not possible to determine the correlations between latent variables using factor scores in the covariance based SEM because factor scores are indeterministic, much the same way as they are indeterministic in common factor analysis (factor scores are deterministic in component-based approaches such as the principal components analysis and the partial least squares based SEM). Some software packages on covariance based SEM method provide factor scores based on certain approximations. The researcher did not opt for an approximate method because the researcher was able to determine the exact correlations due to the fact that the researcher's model was equivalent to the CFA model.

Part I – Important Correlation Matrices

Table E.1: Correlations Between the Measures Belonging to the 4 Latent Variables

Measure	L1	L2	L3	L4	L5	CI1	CI2	CI3	CI4	PO1	PO2	PO3	T1	T2	T3
L1	1.00														
L2	0.56	1.00													
L3	0.54	0.56	1.00												
L4	0.50	0.51	0.58	1.00											
L5	0.58	0.50	0.41	0.48	1.00										
CI1	0.53	0.49	0.41	0.47	0.51	1.00	0.40								
CI2	0.45	0.39	0.40	0.41	0.39	0.40	1.00								
CI3	0.50	0.48	0.40	0.39	0.44	0.51	0.41	1.00							
CI4	0.52	0.46	0.45	0.46	0.44	0.45	0.40	0.47	1.00						
PO1	0.41	0.46	0.42	0.45	0.35	0.41	0.44	0.48	0.39	1.00					
PO2	0.41	0.42	0.41	0.41	0.40	0.39	0.47	0.39	0.40	0.42	1.00				
PO3	0.38	0.39	0.41	0.42	0.34	0.38	0.22	0.34	0.36	0.42	0.36	1.00			
T1	0.27	0.26	0.29	0.17	0.30	0.23	0.13	0.30	0.29	0.22	0.31	0.32	1.00		
T2	0.13	0.10	0.15	0.15	0.12	0.08	0.20	0.10	0.21	0.13	0.22	0.11	0.44	1.00	
T3	0.25	0.26	0.14	0.25	0.25	0.29	0.24	0.25	0.27	0.21	0.24	0.16	0.28	0.20	1.00

Table E.2: Correlations Between the 4 Latent Variables

Latent Variable	Lean Manufacturing System	Continuous Improvement (CI)	Manufacturing Process Outcomes	Taguchi's Quality Philosophy
Lean Manufacturing System	1.000			
Continuous Improvement (CI)	0.938	1.000		
Manufacturing Process Outcomes	0.886	0.931	1.000	
Taguchi's Quality Philosophy	0.453	0.473	0.571	1.000

The correlations in the above table (Table E.2) suggest that two of the 3 predictors that predict manufacturing process outcomes, the Lean Manufacturing System and Continuous Improvement, are strongly related ($r = 0.938$), implying possible collinearity effects. The variance inflation factors (VIFs) of the 3 predictors were computed using the above correlations (using AMOS path modelling); they were found to be as follows (Figure E.1 shows the relevant path models that were used to calculate the VIF values).

The VIF of the Lean Manufacturing System = 8.333

The VIF of Continuous Improvement = 8.547

The VIF of Taguchi's Quality Philosophy = 1.294

All of the above VIF values are below the maximum allowable value of 10.0 prescribed in the literature (e.g. Hair, Black, Babin, & Anderson, 2010). What the above figures suggest is that while one has to acknowledge the fact that two predictors of Manufacturing Process Outcomes are highly strongly correlated, this strong correlation may not be strong enough to upset the results from collinearity.

Hair, J. F., Jr., Black, W. C., Babin, B.J., Anderson, R. E. (2010). *Multivariate data analysis: a global perspective* (7th ed.). Upper Saddle River, NJ: Pearson Education.

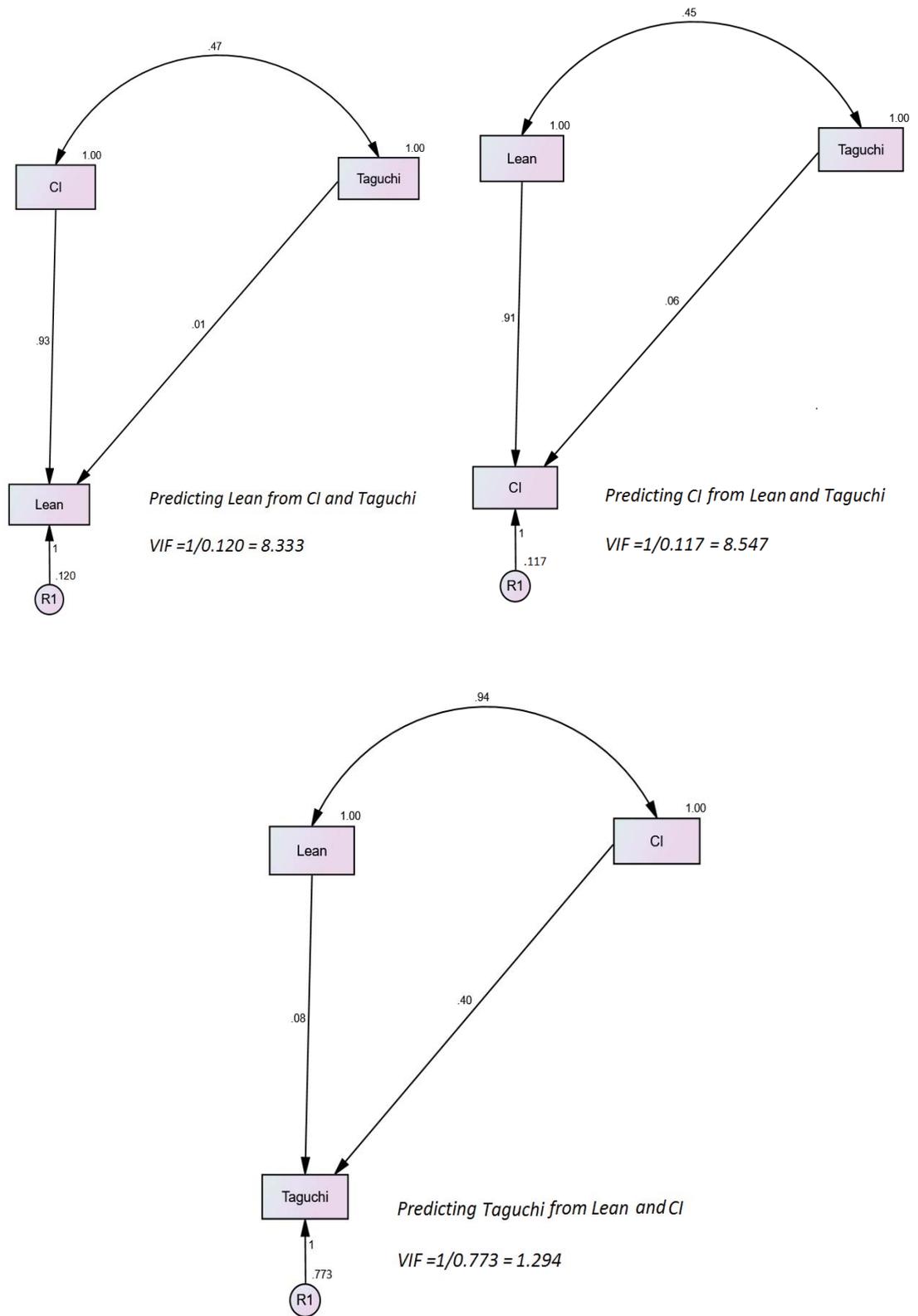


Figure E.1: The relevant path models used for calculating the VIF values of the three predictors of Manufacturing Process Outcomes

Part II – Frequency Distribution Histograms of the Best Case and the Worst Case

This section depicts the frequency (probability) distribution histograms of two measures (there are 15 measures altogether) that represent the best case (the histogram closest to being normal) and the worst case (the histogram being least normal). The researcher concludes (based on the worst case) that there are no major deviations from normality to threaten the robustness of parameter estimates estimated by AMOS. Specific parametric tests (e.g. the Anderson-Darling test) on normality were deemed unnecessary.

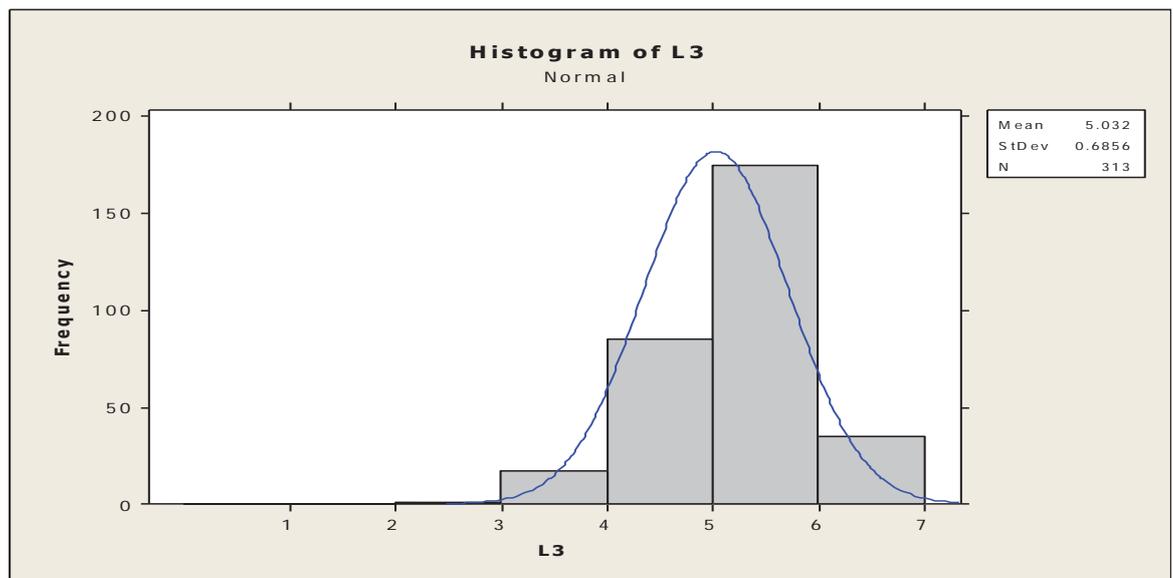


Figure E2: The frequency distribution histogram of the measure that looks closest to being normally distributed

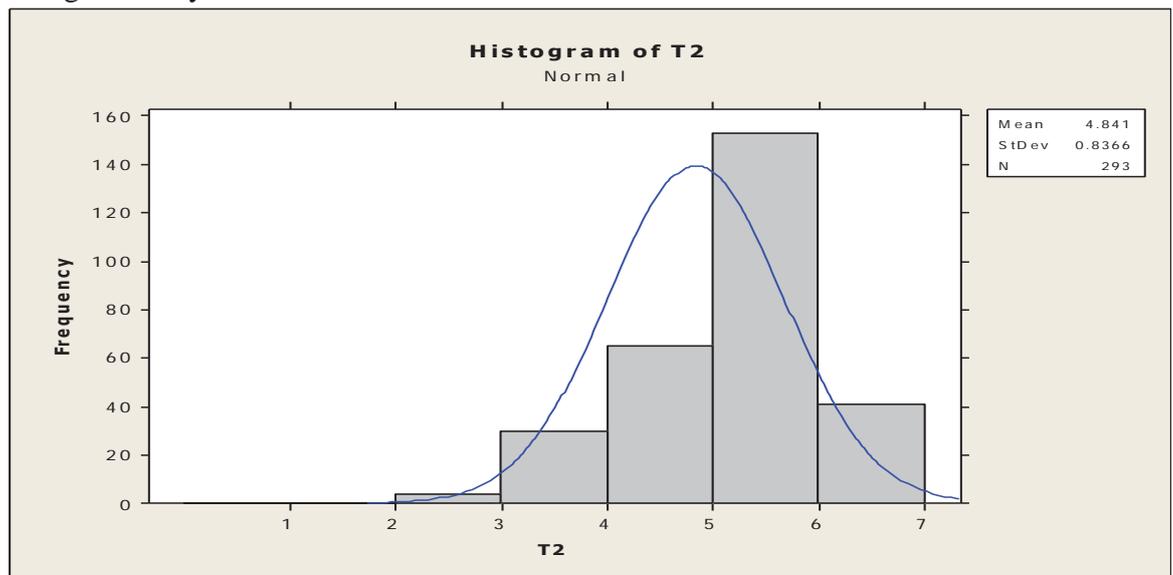


Figure E3: The frequency distribution histogram of the measure that looks furthest to being normally distributed

APPENDIX F: THE FINANCIAL IMPACT OF THE QI EXPERIMENT

This appendix shows how the financial impact of the quality improvement (QI) experiment was calculated.

F.1 The Assumptions

The calculations are based on the following assumptions.

1. The quality loss L in connection with a shipped good can be approximated by a quadratic loss function; thus if 'T' is the target value of the functional characteristic of the product and if Y_i is its functional value at a certain point in time:

$$L = k (Y_i - T)^2; \text{ where } k \text{ is the loss coefficient} \quad (\text{F.1})$$

2. A shipped good is a good that passes quality control; as such, the functional characteristic (back coverage of the garment) of a shipped good shall be within the tolerance band.
3. 50% of the products that do not pass quality control for failing to meet the dimensional tolerance will be scrapped; the remaining 50% shall be reworked to just meet the upper specification limit.
4. The size of a batch is 10,000 (this is the average batch size based on production levels at the time) and the time taken between 2 consecutive batches of production is 1 month.
5. The cost incurred by the organisation in conducting the experiment would be equal to the present value of future (financial) benefits to the case study organisation, and therefore, the next cost incurred by the organisation for the QI project (and therefore for the experiment) is zero.
6. The cost of non-conformance to the tolerance $\Delta 0$ (that is cost of rejection), when the product just fails the tolerance is approximately equal to the shipping cost S , as assumed for a generic product by Taguchi, Chowdhury and Wu (2005).

The calculation shown below follows the exact same method prescribed by Taguchi et al. (2005, p. 448-450).

F.2 Calculation of the Losses Per Batch Prior to the Experiment

The measurements of the 110 samples (subgroups of size 5, taken during 21 intervals) of the product used in process capability analysis prior to the QI experiment are shown in table F.1 below.

Table F.1: Back-Coverage Measurement (Data Used for Control Charts in Section 7.2.2) of the Samples Before the Experiment (all Values are in Inches)

1.6944	2.0668	1.7339	1.8344	1.9364	1.8820	1.9564	1.9431	1.8561	2.1730
2.2199	1.7020	1.7197	1.5574	1.7880	2.1348	1.8945	1.6715	2.0433	2.2752
1.5972	2.3047	1.8617	1.9017	1.6559	1.9850	2.2045	2.3274	1.9229	1.5371
1.8992	1.8460	2.1346	2.2021	1.7522	1.7192	1.8892	2.0438	1.9018	1.6603
1.7924	1.9188	1.9552	1.8054	1.8880	1.6205	2.2978	1.7358	1.8174	1.8122
1.7151	2.2249	1.8870	1.9325	1.9373	1.7579	2.4104	1.6789	1.7284	1.7745
2.1722	2.4440	1.7834	1.6292	1.8258	2.0518	1.9655	2.1130	1.5174	1.9359
2.1738	2.0779	1.9793	2.1208	1.8862	1.7248	2.0003	1.8632	1.5868	2.0604
1.8633	1.5970	2.2055	1.9962	1.9442	2.1202	1.8519	2.4706	1.7958	1.7802
1.8987	1.7020	1.3152	1.8162	1.9503	1.7903	1.9130	1.7690	2.0528	1.4505
1.9420	2.1334	1.9258	1.7278	1.7702	1.7813	1.8015	2.1915	1.9010	2.4432

Table F.2: Number of Passes and Failures to Meet the Specifications Prior to Rework Before the Experiment

Pass	Fail								
Fail	Pass	Pass	Fail	Pass	Fail	Pass	Pass	Pass	Fail
Fail	Fail	Pass	Pass	Pass	Pass	Fail	Fail	Pass	Fail
Pass	Pass	Fail	Fail	Pass	Pass	Pass	Pass	Pass	Pass
Pass	Pass	Pass	Pass	Pass	Fail	Fail	Pass	Pass	Pass
Pass	Fail	Pass	Pass	Pass	Pass	Fail	Pass	Pass	Pass
Fail	Fail	Pass	Pass	Pass	Pass	Pass	Pass	Fail	Pass
Fail	Pass	Fail	Pass						
Pass	Fail	Fail	Pass	Pass	Pass	Pass	Fail	Pass	Pass
Pass	Pass	Fail	Pass	Pass	Pass	Pass	Pass	Pass	Fail
Pass	Fail	Pass	Pass	Pass	Pass	Pass	Fail	Pass	Fail

Total passed = 81 (73.64%); Total Failed = 29 (23.36%); based on the assumptions made, out of the 29 failed items, 15 will be reworked (50%) and 14 will be scrapped (50%).

Table F. 3: Deviations of the 96 Shipped Items (incl. reworked) from the Target (T) Before the Experiment

-0.1806	0.1918	-0.1411	-0.0406	0.0614	0.007	0.0814	0.0681	-0.0189	Scrap
Scrap	-0.1730	-0.1553	Scrap	-0.087	Scrap	0.0195	-0.2035	0.1683	Scrap
Scrap	Scrap	-0.0133	0.0267	-0.2191	0.11	Scrap	Scrap	0.0479	Scrap
0.0242	-0.0290	Scrap	Scrap	-0.1228	-0.1558	0.0142	0.1688	0.0268	-0.2147
-0.0826	0.0438	0.0802	-0.0696	0.0130	Scrap	Scrap	-0.1392	-0.0576	-0.0628
-0.1599	0.2500	0.0120	0.0575	0.0623	-0.1171	0.2500	-0.1961	-0.1466	-0.1005
0.2500	0.2500	-0.0916	-0.2458	-0.0492	0.1768	0.0905	0.2380	0.2500	0.0609
0.2500	0.2029	0.1043	0.2458	0.0112	-0.1502	0.1253	-0.0118	0.2500	0.1854
-0.0117	0.2500	0.2500	0.1212	0.0692	0.2452	-0.0231	0.2500	-0.0792	-0.0948
0.0237	-0.1730	0.2500	-0.0588	0.0753	-0.0847	0.0380	-0.106	0.1778	0.2500
0.0670	0.2500	0.0508	-0.1472	-0.1048	-0.0937	-0.0735	0.2500	0.0260	0.2500

Calculating the average loss L_A due to shipment of N number of products.

$$L_A = \sum_{i=1}^N k (Y_i - T)^2 / N = k * MSD \quad (F.2)$$

Where MSD is mean squares deviation based on the Y values of the N number of observations (note that the reference is the target, not the mean).

From assumption 3 above, $S = k * \Delta_0^2$ and therefore, $k = S / \Delta_0^2$

Substituting k with S / Δ_0^2 in equation E.2 we get:

$$L_A = (S / \Delta_0^2) * MSD \quad (F.3)$$

From the factory records, S (the shipping price of a product) = US\$ 4.00

The dimensional tolerance Δ_0 of the back-coverage = $1/4'' = 0.25$

$$\text{Thus } L_A = 4 / 0.25 * MSD = 16 * MSD; \text{ where the deviation is in inches} \quad (F.4)$$

Thus,

$$\begin{aligned} MSD &= [(-0.1806)^2 + (0.1918)^2 + (-0.1411)^2 + \dots + (0.0260)^2 + (0.2500)^2] / 96 \\ &= 2.11628 / 96 = 0.022045 \text{ inches}^2 \end{aligned}$$

The total variation:

$$S_T = [(-0.1806)^2 + (0.1918)^2 + (-0.1411)^2 + \dots + (0.0260)^2 + (0.2500)^2]$$

$$= 2.11628 \text{ (} df = 96 \text{)}$$

The average of the data deviation from target value:

$$S_m = \frac{(-0.1806 + 0.1918 - 0.1411 + \dots + 0.0260 + 0.2500)^2}{96}$$

$$= (2.8844)^2 / 96 = 0.086664 \text{ (} df = 1 \text{)}$$

Error variation:

$$S_e = S_T - S_m$$

$$= 2.11628 - 0.086664 = 2.02962 \text{ (} df = 95 \text{)}$$

Table F.4: The ANOVA Table – Prior to Experiment

Factor	df	SS	MS	AdjSS	ρ (%)
m	1	0.08666	0.08666	0.06530	3.09
e	95	2.02962	0.02136	2.05098	96.91
Total	96	2.11628	0.02204	2.11628	100.00

Table F.2 reveals the average and the standard mean-squared error of the back-coverage measurements of the thong style garments are contributed approximately similar degrees of contribution (ρ). So the results lead to show the loss is due to both variation and average is off target.

Calculating the Overall Loss – Before the Experiment

The overall loss is the quality loss (cost after the sale is considered as the quality loss) plus factory loss due to rework and scrap (Taguchi & Clausing, 1990). The case study organisation is tracking the cost of product failure through cost of Standard Minute Value (SMV) to manufacturing (US\$ 0.12 for the particular product: the thong style garment). Therefore the cost of the rework at the production is US\$ 0.51 (SMV to manufacture a thong style garment is 4.2338) if the quality characteristic (the back-coverage of the Thong style garments) is beyond the specification limits.

Batch size is 10,000. Assuming that 73.64% (=7364) passes initially and of the remaining 2636, 50% (= 1318) are reworked and the remaining 50% (=1318) are scrapped, foregoing the shipping price of US\$ 4.00.

Overall Loss Associated with the Production Batch of Size 10,000;

$$\begin{aligned}
&= \text{Quality Loss} + \text{Loss Due to Rework} + \text{Loss Due to Scrap} \\
&= 16 * MSD * 7364 + 0.51 * 1318 + 4 * 1318 \\
&= 16 * 0.022045 * 7364 + 0.51 * 1318 + 4 * 1318 = \$8541.61
\end{aligned}$$

F.3 Calculation of the Loss Per Batch After the Experiment

The loss calculation after the experiment was based on the measurements taken from product sewed (manufactured) at the confirmation run. Sixteen pieces of observations (Table F.5, which is a reproduction of Table 7.3 in Chapter 7) were collected during the confirmation run (details in section 7.3.1.1 in Chapter 7) at the optimal machines settings that were derived using Taguchi’s RPD approach. The said 16 pieces of observations were used to calculate the cost savings resulting from the improvement (by reducing the variation of the back-coverage measurement of the thong style garment).

Table F.5: Dimensions Recorded During the Confirmation Run Involving 16 Trials

1.6595	2.1304	1.8791	2.0651	1.9941	1.7223	1.6687	2.1171
1.7391	2.0755	1.9525	2.1185	2.0841	1.7146	1.6477	2.0469
<i>Note: All measurements are in inches</i>							

Table F.6: Number of Passes and Failures to Meet the Specifications Prior to Rework After the Experiment

Pass	Fail	Pass	Pass	Pass	Pass	Pass	Pass
Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
<i>Total passed = 15 (93.75%); Total Failed = 1 (6.25%); it is assumed that the failed item will be reworked to just below the upper specification limit</i>							

Table F.7: Deviations of the 16 Shipped Items (incl. reworked) from the Target (*T*) After the Experiment

-0.2155	0.2500	0.0041	0.1901	0.1191	-0.1527	-0.2063	0.2421
-0.1359	0.2005	0.0775	0.2435	0.2091	-0.1604	-0.2273	0.1719

Average sum of squared deviation of the measurements of the back-coverage at the confirmation run:

$$\begin{aligned} \text{MSD} &= \frac{1}{16} [((-0.2155)^2 + 0.2500^2 + 0.0041^2 + \dots + (-0.2273)^2 + 0.1719^2)] \\ &= 0.03490 \text{ inches}^2 \end{aligned}$$

The total variation:

$$\begin{aligned} S_T &= [(-0.02155)^2 + 0.2500^2 + 0.0041^2 + \dots + (-0.2273)^2 + 0.1719^2] \\ &= 0.55840 \text{ (degree of freedom } df = 16) \end{aligned}$$

The variation due to average of the data deviation from target value:

$$\begin{aligned} S_m &= \frac{(-0.2155 + 0.2500 + 0.0041 + \dots - 0.2273 + 0.1719)^2}{16} = 0.6098^2/16 \\ &= 0.02324 \text{ (} df = 1) \end{aligned}$$

Error variation:

$$\begin{aligned} S_e &= S_T - S_m \\ &= 0.55840 - 0.02324 \\ &= 0.53516 \end{aligned}$$

Table F.8: The ANOVA Table – After the Experiment

Factor	df	SS	MS	AdjSS	ρ (%)
m	1	0.02324	0.02324	0.00000	0.00%
e	15	0.53516	0.03568	0.55840	100.00%
Total	16	0.55840	0.03490	0.55840	100.00%

Calculating the Overall Loss – After the Experiment

Assuming a batch size of 10,000, and assuming that that the process performs as reflected in the confirmation runs subsequent to the experiment, assuming that 93.75% (= 9376) passes initially and of the remaining 624, 50% (= 312) are reworked and the remaining 50% (=312) are scrapped, foregoing the shipping price of U\$ 4.00.

Overall Loss Associated with the Production Batch of Size10,000;

$$= \text{Quality Loss} + \text{Loss Due to Rework} + \text{Loss Due to Scrap}$$

$$= 16 * MSD * 9376 + 0.51 * 312 + 4 * 312$$

$$= 16 * 0.03490 * 9376 + 0.51 * 312 + 4 * 312 = \$6642.68$$

Assuming a zero net cost for the experiment (see assumptions), the total savings for the case study organisation from a batch of 10,000 is \$8541.61 less \$6642.68, which is \$ 2,000.00 aprox.

Savings per batch of 10,000: United States Dollars Two Thousand

APPENDIX G: THE COMBINED ARRAY FOR THE RESPONSE SURFACE APPROACH

This design matrix has been created by combining the inner array and the outer array (see the crossed-array shown in table 7.2 in Chapter 7) as a single array for the purpose of analysing the data for the response surface approach (see section 7.3.2).

Table G.1: Combined Array for the Back-Coverage Measurement

Run order	Std. order	A	B	C	D	E	F	Back-Coverage Measurement
1	2	-1	-1	1	-1	1	1	2.688
2	8	1	1	1	-1	1	1	1.8260
3	4	-1	1	1	-1	1	1	1.9505
4	1	-1	-1	-1	-1	1	1	2.206
5	7	1	1	-1	-1	1	1	1.9150
6	6	1	-1	1	-1	1	1	1.9240
7	3	-1	1	-1	-1	1	1	2.0680
8	5	1	-1	-1	-1	1	1	1.8260
9	9	-1	-1	-1	-1	-1	1	2.8400
10	14	1	-1	1	-1	-1	1	2.0590
11	13	1	-1	-1	-1	-1	1	2.2195
12	12	-1	1	1	-1	-1	1	2.6425
13	15	1	1	-1	-1	-1	1	1.9675
14	16	1	1	1	-1	-1	1	2.2555
15	11	-1	1	-1	-1	-1	1	2.1695
16	10	-1	-1	1	-1	-1	1	1.8230
17	24	1	1	1	1	-1	1	2.4685
18	22	1	-1	1	1	-1	1	2.6765
19	20	-1	1	1	1	-1	1	3.3378
20	21	1	-1	-1	1	-1	1	2.2425
21	23	1	1	-1	1	-1	1	2.5730
22	18	-1	-1	1	1	-1	1	1.9510
23	19	-1	1	-1	1	-1	1	2.8320
24	17	-1	-1	-1	1	-1	1	2.2945
25	31	1	1	-1	-1	-1	-1	1.9345
26	30	1	-1	1	-1	-1	-1	1.4830
27	28	-1	1	1	-1	-1	-1	2.0495
28	26	-1	-1	1	-1	-1	-1	1.4410
29	27	-1	1	-1	-1	-1	-1	1.9720
30	29	1	-1	-1	-1	-1	-1	2.1530
31	32	1	1	1	-1	-1	-1	1.7320
32	25	-1	-1	-1	-1	-1	-1	1.5860
33	34	-1	-1	1	1	-1	-1	2.3585
34	33	-1	-1	-1	1	-1	-1	1.7865

35	38	1	-1	1	1	-1	-1	1.6350	:
36	39	1	1	-1	1	-1	-1	2.5500	
37	37	1	-1	-1	1	-1	-1	2.0315	
38	36	-1	1	1	1	-1	-1	2.4315	
39	40	1	1	1	1	-1	-1	2.1195	
40	35	-1	1	-1	1	-1	-1	2.4070	
41	47	1	1	-1	-1	1	-1	1.4030	
42	48	1	1	1	-1	1	-1	1.9935	
43	43	-1	1	-1	-1	1	-1	1.6770	
44	45	1	-1	-1	-1	1	-1	1.7595	
45	42	-1	-1	1	-1	1	-1	1.8785	
46	46	1	-1	1	-1	1	-1	1.8130	
47	41	-1	-1	-1	-1	1	-1	1.6855	
48	44	-1	1	1	-1	1	-1	1.9015	
49	52	-1	1	1	1	1	1	2.3485	
50	55	1	1	-1	1	1	1	1.7770	
51	51	-1	1	-1	1	1	1	2.3950	
52	49	-1	-1	-1	1	1	1	1.8850	
53	50	-1	-1	1	1	1	1	1.7475	
54	56	1	1	1	1	1	1	2.2345	
55	54	1	-1	1	1	1	1	2.0075	
56	53	1	-1	-1	1	1	1	2.1975	
57	63	1	1	-1	1	1	-1	2.6600	
58	62	1	-1	1	1	1	-1	2.6570	
59	60	-1	1	1	1	1	-1	2.4825	
60	61	1	-1	-1	1	1	-1	2.2215	
61	58	-1	-1	1	1	1	-1	2.6510	
62	59	-1	1	-1	1	1	-1	3.3745	
63	57	-1	-1	-1	1	1	-1	2.7510	
64	64	1	1	1	1	1	-1	2.6955	

APPENDIX H: THE RESULTS OF THE MAIN EXPERIMENT FOR RESPONSE VARIABLES OF SECONDARY IMPORTANCE

The stitch density and ‘roping’ in the product (the thong style women’s brief) were responses of secondary importance to the quality improvement (QI) team. This appendix covers the results of the robust parameter design (RPD) experiment in relation to stitch density and roping. The appendix consists of two parts. Part I covers the results in relation to stitch density while Part II covers results in relation to roping. At the end of Part II, the researcher summarises the results in the light of the results on back coverage (covered in the main body of the thesis), the critical functional characteristic of the product.

Part – 1: Achieving Robustness in Stitch Density

Introduction

The aim of the QI team, and therefore the *objective of the experiment*, was to reduce the variability of stitch density on the sewing contour for the right and left leg hems of the garment (Figure H.1) using the RPD approach. Due to practical reasons explained in appendix D, different parts in a brief get different number of stitches (in general, the parts that are difficult to handle get more stitches, while the parts that are easy to handle get less stitches, because the fabric moves at different speeds depending on the difficulty of sewing) and the QI was interested in finding out whether the stitch density variability within the garment could be minimised, while ensuring that the target stitch density of 17 stitches per inch could be approximately achieved; the QI decided that a plus or minus 2 stitches per inch would be tolerable to the customer.

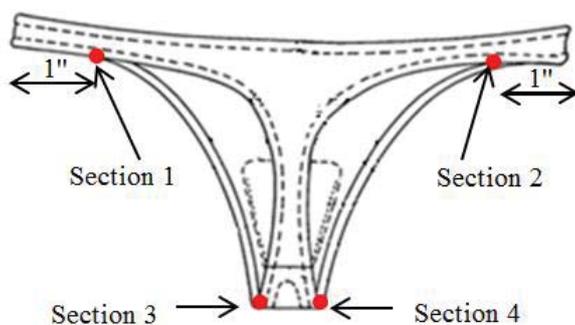


Figure H.1: The 4 locations chosen for taking SPI measurements along the leg hem

The researcher advised the QI team that it is necessary to take measurements from different sections of the garment to study the variability problem. Therefore, the QI team decided that 4 locations of the garment are suitable for recording stitch density (measured in stitches per inch, abbreviated as SPI). These 4 sections are shown in Figure H.1. Four quality controllers were recruited to take measurements from the same garment.

Materials and Methods

For designing the RPD experiment, as mentioned in Chapter 5, six factors were identified by the QI team and these were divided into two sets: *control factors* (factors that can be altered in the experiment as well as in real production) and *noise factors* (factors that are hard or expensive to change in real production). To recap, Table H.1 shows the all six factors and their levels. The crossed array was setup using an L8 orthogonal array for the inner array (the array to which the 3 control factors were assigned) and an L8 orthogonal array for the outer array (the array to which the 3 noise factors were assigned) to obtain the data.

Table H.1: The Control Factors (A, B & C), Noise Factors (D, E & F), and Their Levels

Factor Description	Label	Level 1 (-1)	Level 2 (+1)
SPI adjuster screw length	A	20.5 mm	21 mm
Presser foot pressure	B	21 mm	22 mm
Feed-dog height	C	1	4
Fabric type	D	Low g/m ²	High g/m ²
Presser foot condition	E	Old	New
Handling techniques	F	Low Experience	High Experience

Table H.2 shows the raw data taken by the 4 quality controllers at each of the 4 locations of the garment, while Table H.3 shows the variance data only; the variance is the response. The two levels of each factor are represented as -1 and 1 in Tables H.1 through to H.3.

Table H.3: The Crossed Array and the Response

Inner Array (Control Factors)			Outer Array (Noise Factors)/Variance of Stitch Density															
A	B	C	D	-1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	Mean SPI (from Table G.2)	Standard Deviation of Variance	SNR $-10 \log \left(\frac{1}{N} \sum_{i=1}^N Y_i^2 \right)$
-1	-1	-1	3.9833	2.1601	2.5559	1.48724	1.13229	0.34359	0.9602	0.4958	0.4958	0.9602	0.4958	0.4958	0.4958	20.61328	1.2150	-5.9996
-1	-1	+1	3.5406	1.0822	3.8666	0.81016	0.88516	2.2542	0.8573	3.8747	3.8747	0.8573	3.8747	3.8747	3.8747	19.76367	1.4179	-8.0387
-1	+1	-1	3.2656	1.8656	4.3768	1.85391	1.63229	1.5581	9.4823	0.2991	0.2991	9.4823	0.2991	0.2991	0.2991	21.49609	2.8739	-12.169
-1	+1	+1	9.8958	1.9184	2.2039	1.98099	1.65182	0.4490	3.0581	0.5581	0.5581	3.0581	0.5581	0.5581	0.5581	20.43359	3.0245	-11.868
+1	-1	-1	3.0625	1.4958	2.4208	2.39174	1.06563	0.6406	1.0656	0.2914	0.2914	1.0656	0.2914	0.2914	0.2914	18.39258	0.9738	-5.1128
+1	-1	+1	5.2333	0.5791	3.2322	0.14583	1.70729	0.5417	0.9458	0.6247	0.6247	0.9458	0.6247	0.6247	0.6247	17.48242	1.7537	-7.2719
+1	+1	-1	3.3708	1.7489	3.0080	1.75391	1.01641	0.3917	2.0667	1.7977	1.7977	2.0667	1.7977	1.7977	1.7977	19.47852	0.9658	-6.4389
+1	+1	+1	3.4872	1.5768	2.6333	1.69896	2.25417	1.4310	0.8727	0.9958	0.9958	0.8727	0.9958	0.9958	0.9958	18.04297	0.8793	-6.2001

The SNR statistic Table H.3 corresponds to “smaller the better” performance characteristic because the objective is minimise the variability of stitch density along the leg hem of the garment:

$$SNs = -10 \log \left(\frac{1}{n} \sum_{i=1}^n Y_i^2 \right) \quad (H.1)$$

The signal-to-noise ratio (SNR) values for each control factor combination were computed based on the Y_i (Morse et al.) values (measurements from 4 locations from 4 operators, although occasionally, there were missing data as shown in the blank cells in Table H.2) for each noise factor combination. The best control factor combination is the factor combination that results in the largest SNR, calculated as per eq H.1 above (Roy, 2010).

Results and Discussion

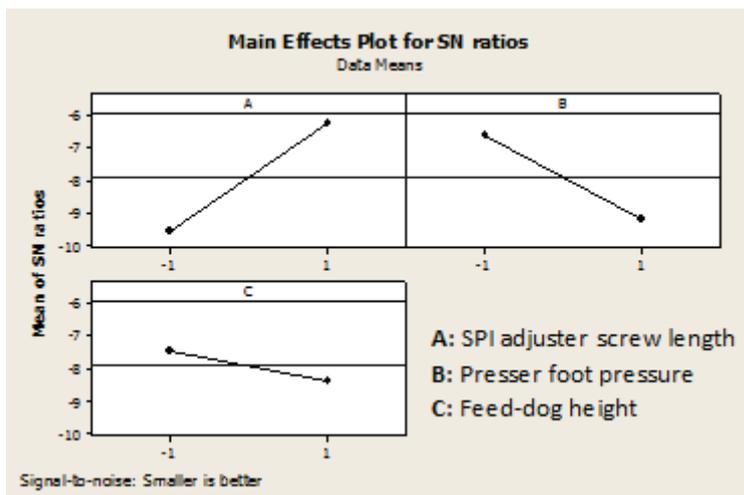


Figure H.2: The main effect plots of the SNR

Response Table for Signal to Noise Ratios			
Smaller is better			
Level	A	B	C
1	-9.519	-6.606	-7.430
2	-6.256	-9.169	-8.345
Delta	3.263	2.563	0.914
Rank	1	2	3

Response Table for Means			
Level	A	B	C
1	2.386	1.742	2.033
2	1.736	2.380	2.089
Delta	0.650	0.638	0.056
Rank	1	2	3

A: SPI adjuster screw length
B: Presser foot pressure
C: Feed-dog height

Figure H.3: Response table for SNR and mean

Figures H.2 and H.3 show the main effects plots of the control factors and the SNR is highest when the factor A at high level and factor B and factor C at their low setting. It is not surprising that factor A (Figure H.2), the SPI adjuster screw, emerges as the dominant factor because by definition, factor A is the adjustment factor for (mean) stitch density. From a practical perspective, therefore, factor A adjusts both the SPI mean and the SPI variance.

Figure H.4 shows a possible practically significant two-way interaction between a control factor and noise factor (curiously, the higher ranked control factors A and B do not show any possible practically significant interactions with the noise factors). The figure shows that the variation created by noise factor E could be minimised when the feed-dog-height (factor C) is set between -1 level (setting 1) and the +1 level (setting), say at setting 2. However, the overall variability reduced by adjusting the feed dog height (Factor C) is likely to be practically insignificant because factor C is the least ranked factor based on the SNR.

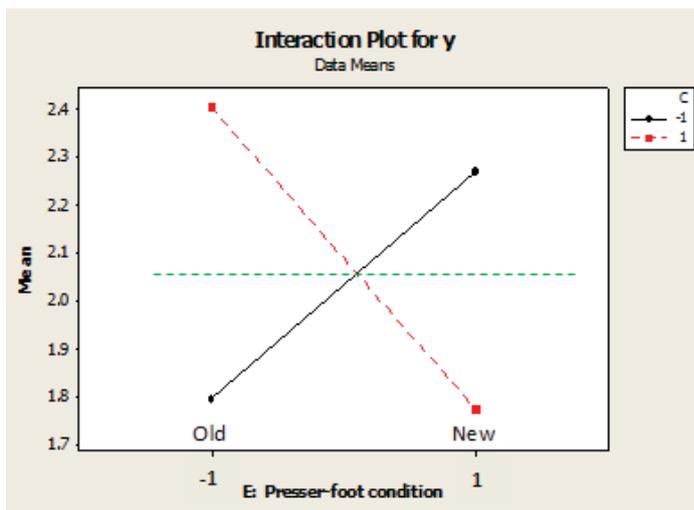


Figure H.4: The interaction plot between factor C (Feed-dog-height) and factor E (Presser-foot-condition)

Part II – Achieving Robustness (Minimising) in Roping

Introduction

Roping is a particular nonconformity that quality controllers come across in sewed fabric, particularly in “thong style” panties. Roping occurs due to twisting of the fabric while sewing. The shape—narrow width of the back side of the product—of the thong style panty is thought to be the main reason for roping. Figure H.5 illustrates some panties with roping (the nonconformity is circled) and without roping.



Figure H.5: Panties with and without roping

Under the existing quality control procedures, the sewed items (panties) will be inspected by quality controllers for roping under standard lighting in a viewing area and each panty would be categorized either as a conforming item or a nonconforming item. The nonconforming items are often restored, through rework.

Material and Methods

The researcher used a numerical measurement scale to measure the severity of roping by converting subjective assessments on roping to numerical codes using a 5-interval assessment scale, facilitated by 5 specimens visually being displayed on dummy models (Figure H.6). These specimens represent: no roping (specimen 1), low roping (specimen 2), average roping (specimen 3), moderate roping (specimen 4), and severe roping (specimen 5). The 4 quality controllers used in taking the SPI measurements were assigned to make assessments on the level of roping present in the garments sewed in the experiment. The assessors (quality

controllers) were asked to rate the level of roping at *four portions of the garment*, two in the front and two in the back. Prior to this, the quality controllers were trained to use the scale developed by the researcher by randomly assigning them to rate 20 garments for level of roping present, to ensure that there is consistency in the ratings given by the four quality controllers.

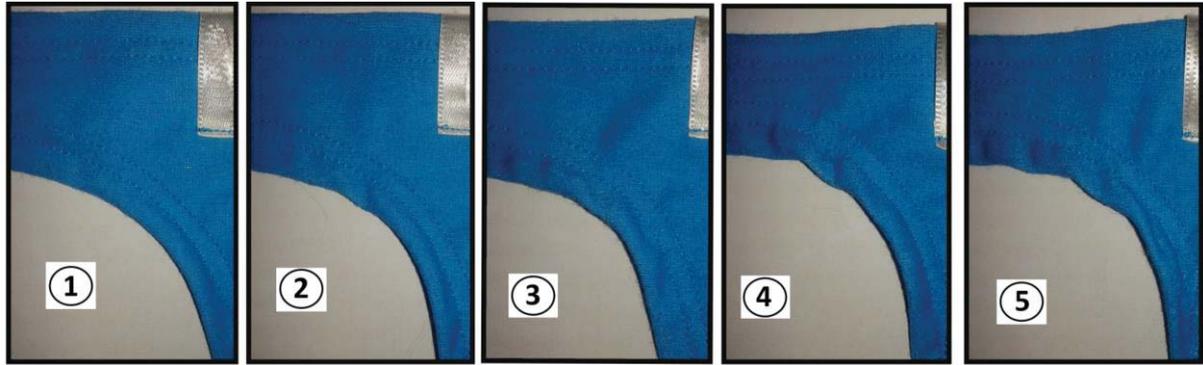


Figure H.6: Measurement scale used to measure the roping in Thong style garment

Table H.4 shows the mean roping score (total score divided by 4*4) of the response data for the roping at each factor setting. The two levels of each factor in Tables H.4 are represented as -1 and +1 in the data matrix (Table H.4) as usual.

The last two columns in The SNR statistic Table H.4 corresponds to “smaller the better” performance characteristic because the objective is minimise roping (hence the roping score) along the leg hem of the garment:

$$SNs = -10 \log \left(\frac{1}{n} \sum_{i=1}^n Y_i^2 \right) \tag{H.2}$$

Table H.4: The Crossed Array and the Response

Inner Array (Control Factors)			Outer Array (Noise Factors)/Y (Mean roping score)												Standard Deviation	SNR $-10 \log \left(\frac{1}{n} \sum_{i=1}^n Y_i^2 \right)$	
A	B	C	D	-1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1
-1	-1	-1	2.4375	2.3125	2.1666	2.1250	1.8333	3.0000	1.9167	2.3750	0.3628	-7.2196					
-1	-1	+1	3.5000	1.8125	3.0000	2.3125	2.2500	1.7500	2.3333	2.0000	0.6006	-7.7317					
-1	+1	-1	1.7500	1.8750	2.7500	2.4375	2.5000	2.1667	1.9167	2.1250	0.3471	-6.9037					
-1	+1	+1	1.6250	1.6875	2.0833	2.1875	1.2500	2.0833	1.58333	1.8750	0.3183	-5.2079					
+1	-1	-1	2.3125	2.4375	2.0000	2.5000	2.1667	1.9167	2.2500	2.2500	0.1995	-6.9932					
+1	-1	+1	2.4375	2.3750	2.5000	2.7500	2.3333	2.6667	2.2500	2.0000	0.2363	-7.6912					
+1	+1	-1	2.0625	1.7500	1.5833	1.9375	2.5000	2.3333	2.3333	2.1250	0.3124	-6.4384					
+1	+1	+1	2.1250	1.3125	1.4166	2.1875	2.2500	1.7500	1.5833	1.8750	0.3579	-5.3112					

Results and Discussion

Figure H.7 shows the main effect plots of the control factors for the response SNR. The SNR is highest when factor A and B and C are set at high level. Factor B is the most significant factor while factor A is the least significant factor, based on Figure H.7.

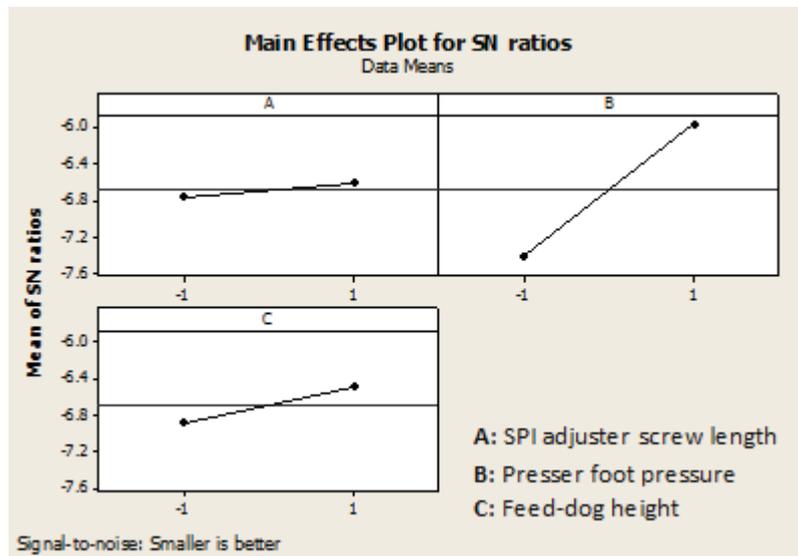


Figure H.7: The main effect plots of the SNR

Figure H.8 shows the rank of the three control factors based on the SNR and the mean response values. Like Figure H.7, Figure H.8 also shows that Factor A is the factor that has the least significant impact on the SNR, factor C is the second most influential factor, and factor B is the most important factor. In addition, Figure H.8 shows that the factor rankings based on the SNR is the same as factor ranking based on the mean.

Response Table for Signal to Noise Ratios			
Smaller is better			
Level	A	B	C
1	-6.766	-7.409	-6.889
2	-6.609	-5.965	-6.486
Delta	0.157	1.444	0.403
Rank	3	1	2

Response Table for Means			
Level	A	B	C
1	2.157	2.321	2.192
2	2.133	1.969	2.098
Delta	0.023	0.352	0.094
Rank	3	1	2

A: SPI adjuster screw length
B: Presser foot pressure
C: Feed-dog height

Figure H.8: Response table for SNR and mean

Figures H.9 and Figure H.10 show possible practically significant two-way interactions between control factors and noise factors. These two figures show that the variation created by noise factors N1 and N3 can be minimised when factor control factor C set between -1 (feed dog height setting 1) and 1 (feed dog height setting 4).

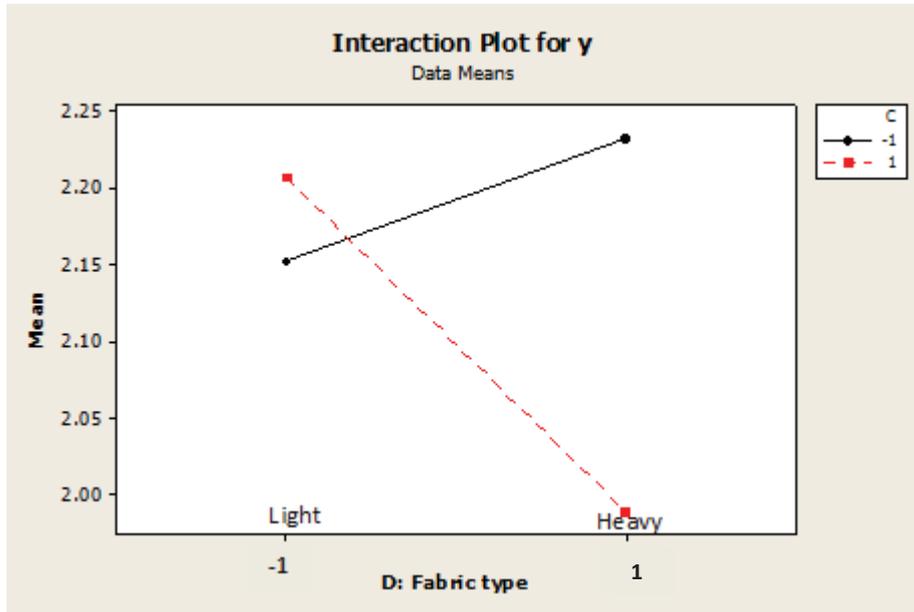


Figure H.9: The interaction plot between factors C (feed-dog-height) and D (fabric type)

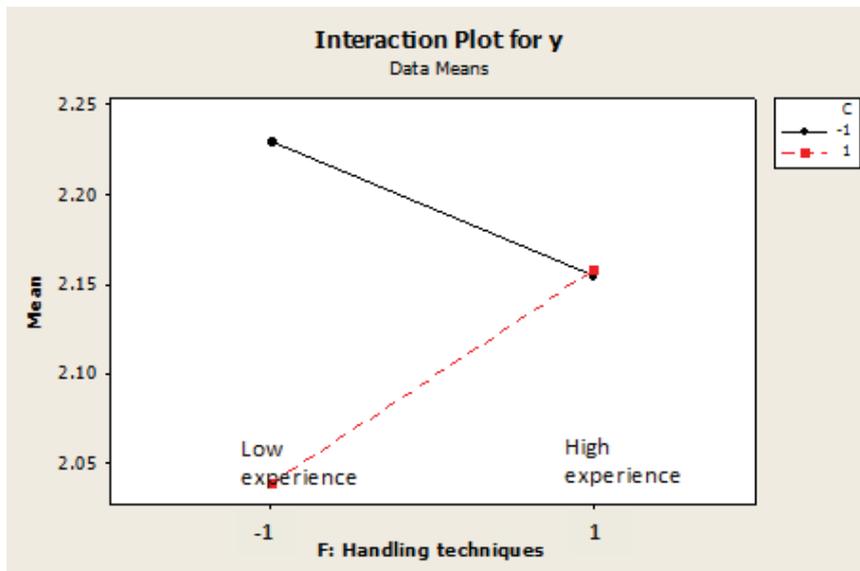


Figure H.10: The interaction plot between factors C (feed-dog-height) and F (handling techniques)

Conclusion

Table H.5 compares the robust setting for the primary response variable of interest, back coverage (details in Chapter 7), with the ideal robust settings for the secondary variables of interest, SPI (variability) and roping, based on the analysis covered in this appendix.

Table H.5: Optimum Factors Setting Based on Taguchi Methods for Three Responses: Back-coverage, SPI, and Roping

Response Type	Optimum Control Factor Setting Based on Taguchi Methods		
	Factor A <i>SPI adjuster screw length</i>	Factor B <i>Presser foot pressure</i>	Factor C <i>Feed-dog height</i>
Back-coverage <i>(The most important response)</i>	High	Low	Low
SPI variability (stitch density variability) <i>(The second most important response)</i>	High	Low	Low (based on SNR) Middle (based on the C*E interaction)
Roping <i>(The least important response)</i>	High	High	High (based on SNR) Middle (based on C*E and C*F interactions)
The noise factors: Fabric type (D), Presser foot condition (E), and Handling techniques (F)			

The results (Table H.5) show that there is no conflict in the setting of the first control factor (Factor A: SPI adjuster screw), in that setting it at high setting optimises all three response variables. However, the results show that there is a slight conflict in the setting of the third control factor (Factor C: feed-dog-height) in that setting it at the low setting optimises the most important response variable as well as the second most important response variable but may compromise the least important response variable. On the same token, the results show that setting the second control factor (Factor B: Presser foot pressure) at the low setting optimises the most important response variable as well as the second most important response variable but may

compromise the least important response variable. This is a typical problem in multi-response optimisation (a trade-off is required). Given the priority levels assigned to response variables, the researcher concludes that the robust setting for back coverage is the most suitable robust setting, overall.

APPENDIX I: A SAMPLE OF QUALITY TOOLS COLLECTED FROM THE FACTORY BELONGING TO THE CASE STUDY ORGANIZATION

MOS Manual Page 1 of 1
 MAS INTIMATES
 1 වන නිරාකරණ කිරීමේ පටිපාටි (PDCA)
 DATE (සැ/ස/ව) 2018-02-06
 Department / Section / Module (අංශ) - තනි පැහැ
 Issue No: 1
 Issue Date (yy/mm/dd):
 Document No:

THEME (පේශය)
 2018-02-06 හි 10 Line pass rate හි 5% ක් 90 පැහැ කඩ කට ගැනීම

Standard/මිලියා
 90%
 Current Situation (වර්තමාන තත්වය)
 52.21%
 Discrepancy (පරතරය)
 37.79%
 Extent (පරාසය)
 2018-01-31 දින සිට
 Rationale (පරිමාණය) 10 Line pass rate හි 5% ක් 90 පැහැ කඩ කට ගැනීම තුළින්
 අනාරක්ෂිත FM හි ප්‍රධාන හේතු

COUNTERMEASURES (සමඛ පිටුපාටි ක්‍රමය)
 Evaluate Possible Countermeasures (සමඛ පවතින සියලුම ක්‍රමයන්)

Possible Countermeasures (සමඛ පවතින ක්‍රමයන්)	Effectiveness (ප්‍රභවය) - H/L/M	Feasibility (සමඛය) H/L/M	Impact (ප්‍රභවය) - H/L/M
තනි පැහැ කඩ කට තුළ ප්‍රධාන හේතු	H	H	H
තනි පැහැ කඩ කට තුළ ප්‍රධාන හේතු	H	M	H
ප්‍රධාන 10cm member ට පැහැ කඩ කට			
ප්‍රධාන 10cm member ට පැහැ කඩ කට			
ප්‍රධාන 10cm member ට පැහැ කඩ කට			

 Most Appropriate Countermeasures (සමඛ පවතින සියලුම ක්‍රමයන්)
 10 Line pass rate හි 5% ක් 90 පැහැ කඩ කට ගැනීම තුළින් ප්‍රධාන හේතු

TARGET (ලැබීමට)
 Do What (කළ යුතුය) ක්‍රමයන් හි ප්‍රමාණය
 To What (කුමක් සඳහා) 10 Line pass rate
 How Much (කොපමණ ප්‍රමාණයක්) 37.79%
 By When (කොපමණ වේලාවක) 2018-02-27

CAUSE ANALYSIS (හේතු විග්‍රහණය)

Potential Causes (හේතු වැනි හේතු)	Check Method (විග්‍රහණය කිරීමේ ක්‍රමය)	Evaluate (මැනීම)
clean garment	analyzed	42.22%
Appearance		23.24%
measurement		12.22%

 Most Likely Cause's (විශේෂයෙන්ම හේතු)
 clean garment and Appearance

IMPLEMENTATION PLAN (ක්‍රියාට නැංවීමේ ක්‍රමය)

What Action is to Be Taken Immediately (කළ යුතු ක්‍රියා)	Who is Responsible (කවුන්ගේ වගකීම)	Schedule Timing (yy/mm/dd) - ක්‍රියා කළ යුතු කාලය
තනි පැහැ කඩ කට තුළ ප්‍රධාන හේතු	Hemantika	2018-02-10 2018-02-31
ප්‍රධාන 10cm member ට පැහැ කඩ කට	Tharangaika	
ප්‍රධාන 10cm member ට පැහැ කඩ කට	Wanara	2018-02-07 2018-02-09
ප්‍රධාන 10cm member ට පැහැ කඩ කට	Kamal	2018-02-07 හි ප්‍රධාන
ප්‍රධාන 10cm member ට පැහැ කඩ කට	Wanara	
ප්‍රධාන 10cm member ට පැහැ කඩ කට	Kanitha	2018-02-07 හි ප්‍රධාන

CAUSE ANALYSIS TOOL (5 WHY / FISHBONE) (හේතු විග්‍රහණය කිරීමේ ක්‍රමය)
 1. ප්‍රධාන හේතු කුමක් වේ?
 2. ප්‍රධාන හේතු කුමක් වේ?
 3. ප්‍රධාන හේතු කුමක් වේ?
 4. ප්‍රධාන හේතු කුමක් වේ?
 5. ප්‍රධාන හේතු කුමක් වේ?

FOLLOW-UP / VERIFICATION / STANDARDIZATION (කළ යුතු ක්‍රියා & සිහිපත් කිරීම)
 PLAN
 DO
 CHECK
 ACT
 month

H - High L - Low M - Medium

Figure I.1: PDCA problem solving sheet

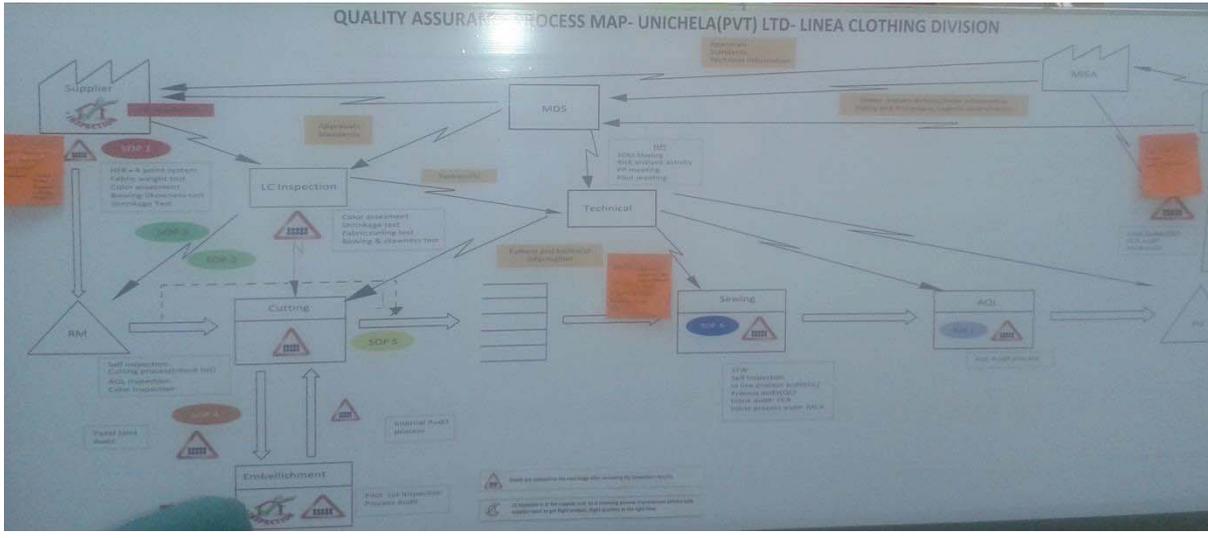


Figure I.2: A quality assurance process map

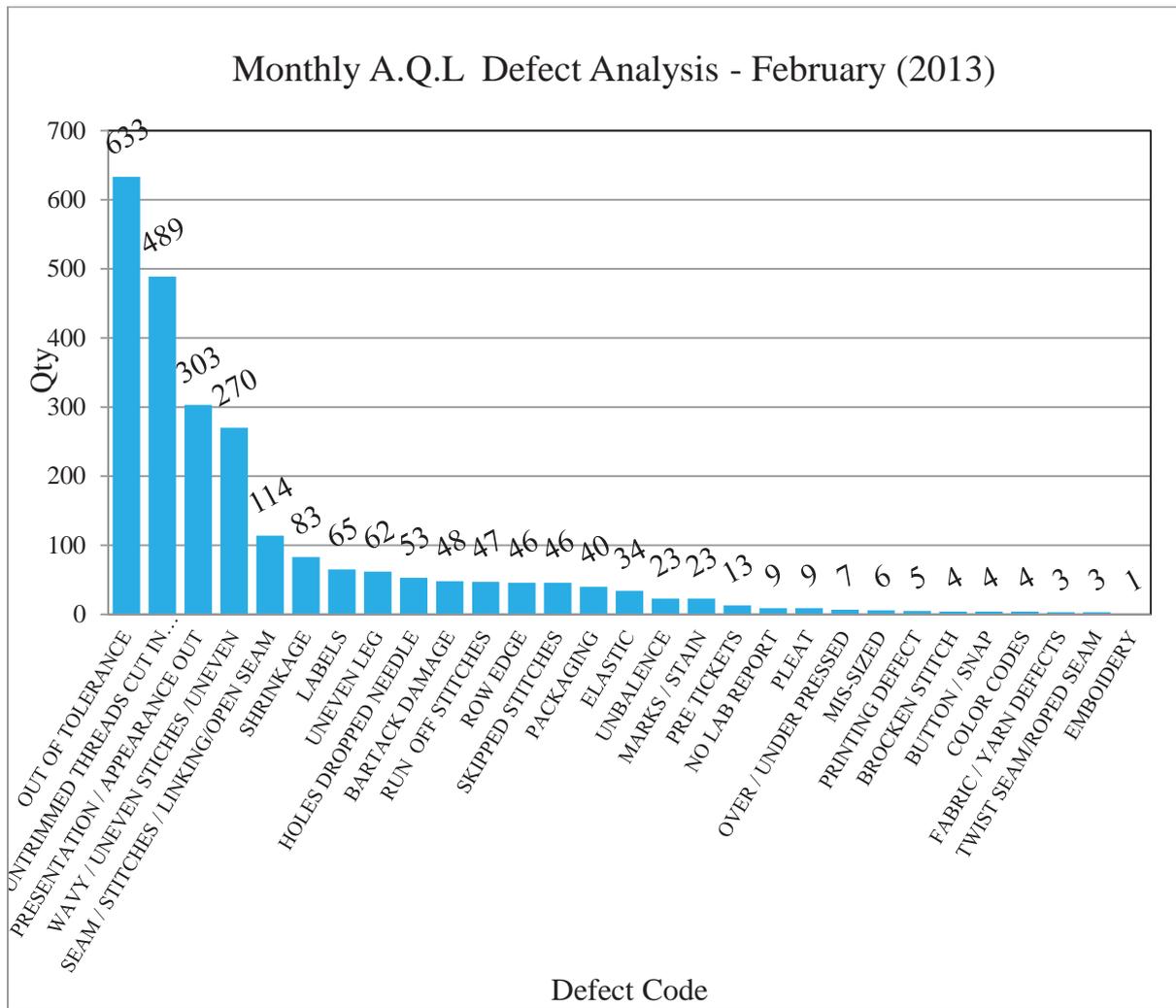


Figure I.3: The AQL quality level for February 2013 based on defects analysis

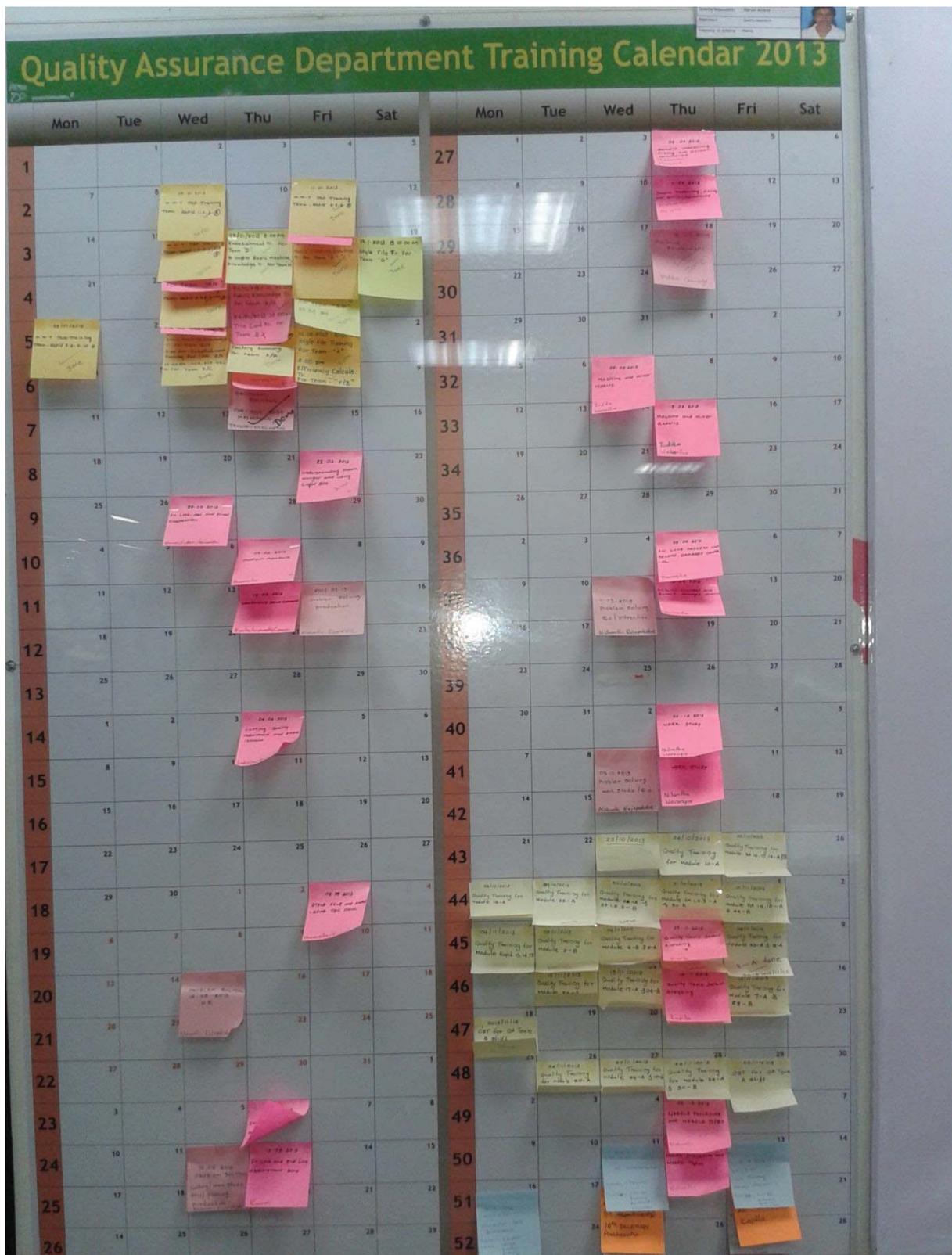


Figure I.4: Quality assurance department training calendar

"6S" සංකල්පය අපේ ජීවිතේ කොටසක් කර ගනිමු !!!

"6S" යනු ඵලදායීතාවය ඉහළ යන පරිදි ඔබගේ වැඩ කරන වටපිටාව ක්‍රමානුකූලව හා පුරුද්ධිමත් කළයුතුයන් සඳහා ගැනීමයි.

"6S" ක්‍රමයේ ලොවට හඳුන්වා දුන්නේ ජපානය විසිනි. "6S" ක්‍රමයේ අවට පරිසරය සහ ජීවන රටාව ක්‍රමවත්ව සංවිධානය කිරීමට හා පවත්වාගෙන යාමට උපකාරීවන අදියර පහක් හඳුන්වාදෙයි...

• SEIERI	- සෙයිට්	- SORT
• SEITON	- සෙයිනෝන්	- SET IN ORDER
• SEISO	- සෙයිසෝ	- SHINE
• SEIKETSU	- සෙයිකෙත්සු	- STANDARDIZATION
• SHITSUKI	- ෂිට්සුකි	- SUSTAIN
• SAFETY	- සේෆ්ටි	- SAFETY

සිංහල අර්ථයන්

- 1) **සෙයිට් - (Sort) - වර්ගීකරණය**
 - අවට ඇති සියළුදෑ වර්ග කිරීම.
 - ඒවා වෙන් වෙන්ව තැන්පත් කිරීම.
 - යල්පැන ගිය අනවශ්‍ය සියළුම දේ ඉවත දැමීම.
- 2) **සෙයිනෝන් - (Set in order) - සංවිධානය**
 - ඔහුම භාණ්ඩයක් පහසුවෙන් හඳුනා ගත හැකි පරිදි නියමිත ස්ථාන වල තැබීම. සෑම භාණ්ඩයකටම ස්ථානයක් තිබීම සහ නියමිත ස්ථානයේ නියමිත භාණ්ඩය තිබීම.
- 3) **සෙයිසෝ - (Shine) - පිරිසිදුබව**
 - පිරිසිදු කිරීමේ වගකීම වෙන් කර දැකීම.
 - පිරිසිදු කිරීමේ කාල සටහනක් සකස් කර ගැනීම.
 - පවුලකා ඉලක්කයක් ඇති කර ගැනීම.
 - දිනපතා සේවා ස්ථානයෙහි මිනිත්තු 5ක් පිරිසිදු කර ගැනීම සඳහා වෙන් කර ගැනීම.
- 4) **සෙයිකෙත්සු - (Standardization) - ප්‍රමිතිකරණය**
 - ඉහත පියවර 3 සඳහා නියමිත ඒකාකාරී ප්‍රමිතියක් හෝ සම්මුතියක් ඇති කර ගැනීම. පරීක්ෂා කර ගැනීමේ ලැයිස්තුවක් සකස් කර ගැනීම.
- 5) **ෂිට්සුකි - (Sustain) - විනය හා පුහුණුව**
 - ඉහත පියවර පවත්වා ගැනීම සඳහා සියල්ලන් පුරුදු පුහුණු කිරීම.
- 6) **සේෆ්ටි - (Safety) - ආරක්ෂාව**
 - කාර්යය ස්ථානයේ ආරක්ෂාව පිලිබඳ සැලකිලිමත්වීම.



Make things easy to find.



Get rid of unnecessary things.

Figure I.6: An extract from a handout given to new recruits in their induction training program. This extract shows the 6S (The 5S system + Safety) principles.

Standard procedure: Broken Needle Replacement Procedure flow

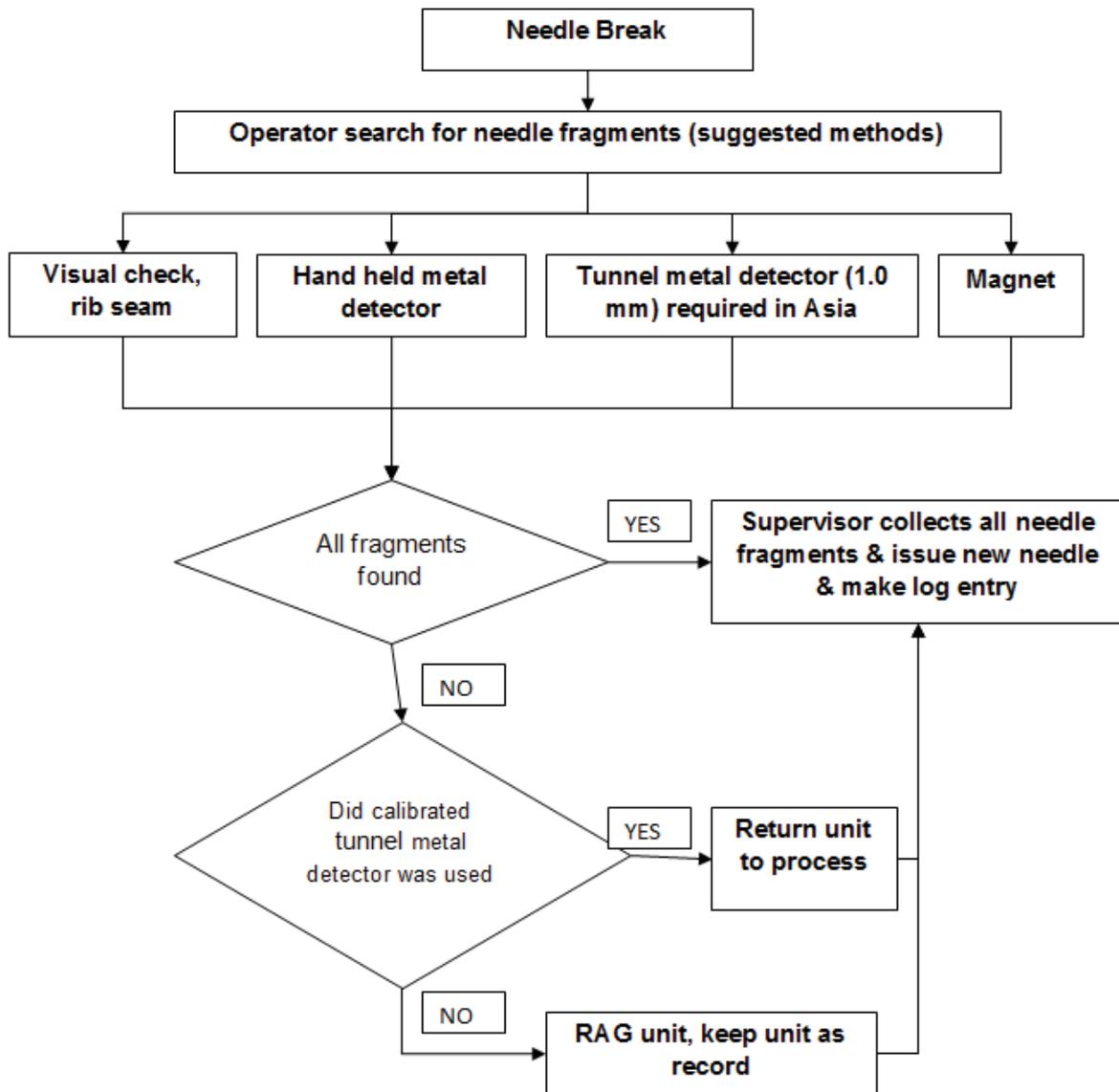


Figure I.7: Flow chart showing the standard procedure to replace the broken needles



Office Area 5S Audit Sheet

Marking scheme

The same marking scheme would apply;

No Violations - 05 Points

- **1 Violation - 04 Points**
- **2 Violations- 03 Points**
- **3 Violations- 02 Points**
- **4 Violations- 01 Points**
- **5 Violations or more - No points would be awarded for the relevant topic.**

	Title/ Area	Number of deviations	Marks
1	- Work Stations are neat and tidy. - Only necessary items are available	01	
2	Work stations has an identification number		
4	All drawers are neat and tidy with only the relevant items; - 1 st drawer- stationary on the designated template - 2 nd drawer- Stationary, books, files - 3 rd drawer- Personal belongs		
5	All files are labeled		
6	File index is maintained		
7	The files have a content sheet and only relevant documents are included		
8	File rack is clean and is not over filled		
9	Display boards and graphs are updated		
10	All out dated information (posters, graphs have been removed) Name of the person who updates information is mentioned and displayed		
11	Cupboards - All items have been arranged properly and neatly stacked		
	Stored items are named		
	No unnecessary items are found		

Figure I.8: 5S audit sheet